REPORT OF
DEPARTMENT OF DEFENSE
ADVISORY GROUP ON ELECTRON DEVICES

SPECIAL TECHNOLOGY AREA REVIEW

ON

VACUUM ELECTRONICS TECHNOLOGY FOR RF APPLICATIONS

Compiled from the STAR held on
December 11-12, 2000

OFFICE OF THE UNDER SECRETARY OF DEFENSE
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EXECUTIVE SUMMARY

Vacuum Electronic (VE) devices are used for RF power amplification in many military radar, electronic attack, and communication systems. VE technology has the capability to generate medium-to-very-high RF power over multi-octave bandwidths with high efficiency; it also provides superior performance in the generation of medium-to-high RF power at millimeter-wave frequencies. These performance advantages make the development of advanced VE devices attractive for use in new military systems. However, DoD funding cuts for VE S&T since 1995 are severely limiting the rate of technology advancement and the development of new devices. Further cuts threaten the entire VE S&T program and the U.S. technology base.

The principal recommendation of this STAR is to increase S&T investment in Vacuum Electronics to a minimum level of $27M per year for a minimum of 5 years. Included in this investment plan are the following program elements:

1. Basic Research (6.1) funding of $5M per year, including the MURI program, is needed to strengthen VE technology in the Universities, Government labs, and industry. This funding will continue the development of new microwave and millimeter-wave RF device concepts, improve the understanding of device physics, help to sustain the University VE community, and assure a continuing source of trained engineers and scientists that are essential for a strong U.S. industrial base.

2. Increase Applied Research (6.2) funding to a level of $12M per year to continue and expand the current efforts to develop VE devices needed for future military systems, to continue the development of the advanced modeling and simulation environment and tool set, and to develop sub-component and materials technologies.

3. Advanced Development (6.3) funding of $10M per year is needed to mature device designs and manufacturing processes of VE devices for targeted systems applications, and to assure that devices meeting the performance and affordability requirements of future DoD systems will be available when needed.

In addition to the critical need for increased S&T funding, investments are needed to mature Microwave Power Module (MPM) designs for identified electronic attack (EA), towed decoy, and mobile communication systems. These efforts are directed at improvements in design to reduce the production cost and demonstration of life and reliability. ManTech funding of $5M to $7M over 3 years is recommended to meet system insertion targets including SMART-T, HPFOTD, and EA jammers.

Continued Title III funding of $3M per year is needed to address supply chain issues for critical materials and components used in the production of VE devices. The improvements achieved with this program can significantly improve the performance and cost of VE devices and assure the continued long-term availability of these critical components.

DoD funding is also recommended to modernize and upgrade existing transmitters that use VE devices such as AN/ALQ-99, AN/ALQ-184, and TPS-25. This can provide enhanced system performance and reliability. It can also result in significant operating cost savings over the projected systems life of 30 years or more. The recommended funding is $2M to $4M per system.

Since the beginning of the S&T initiative in 1990, VE technology is continuing to make dramatic advances in device performance, reliability and life. The improvements in RF power, high frequency performance, bandwidth, efficiency and reliability, since 1980, include:

- Average RF power capability at frequencies above 40 GHz has increased by a factor of 10 to 50 times.

- Bandwidth (Fmax/Fmin) has increased by a factor of 3 to more than 3 octaves.

- Efficiency has increased by nearly a factor of 2 to 73% for narrow-band devices and 50% for broadband devices.

- Reliability has been increased by factors of 10 to 100 for military and space applications, respectively. Current space TWTs are achieving in-orbit MTTF of greater than 10 million hours.

These advances are being enabled by the development of a computer modeling and simulation environment with advanced tools, new device concepts, and improved component designs that are the direct result of the Tri-Service VE Initiative (1990 to 1995) and the Navy's VE S&T program (1996 to 2000).

However, DoD funding of VE S&T has decreased from $35M (FY01$) in FY93 to $7.7M in FY01. These funding cuts threaten to dismember the entire VE S&T program and to erode the U.S. technology base. At this budget level, there is no funding for VE industrial S&T programs to develop advanced devices for future military applications. Title III funding for FY01 is $3M and $2M for FY02. Funding for these programs has been sporadic.

VE devices are currently used in 272 DoD systems, consisting of hundreds of unique designs. Many of these systems will continue to be in use for the next 30 years or more. The number of VE devices in use will increase to more than 190,000 (from 185,000 today) over the next 5 years as new systems are deployed.

The future military insertion opportunities for VE devices were identified in the RF Transmitter Requirements Workshops conducted last year by a Tri-Service group led by ONR and NRL.

To support new systems including those listed in Principal Finding #11, advanced VE devices are needed, requiring the development of new designs and technologies. Examples include:

- High-efficiency medium-to-high RF power (>50 watts) millimeter-wave (>30 GHz) amplifiers for high-data-rate satellite communication terminals and data links on small platforms.

- Microwave Power Modules with medium-to-high RF power, high efficiency, and ultra broad bandwidth (>2 octaves) for EA transmitters and towed decoys.

- High-power pulsed millimeter-wave compact amplifiers for advanced missile seekers.

- Very high power (kilowatts and higher) pulsed amplifiers for radar and directed energy applications.

INTRODUCTION

Military superiority is becoming increasingly dependent on the development of high performance electronic systems for detection, weapons guidance, electronic protection, and network-centric communications. Future missions will require advanced RF transmitters with longer ranges (higher RF power and improved signal quality), smaller size (higher efficiency), lower risk, and affordable cost.

These systems are the "eyes" of the warfighter and their capability is critically dependent on the performance of the RF transmitter power amplifiers that are used. The two RF amplifier choices that are available to system designers are Vacuum Electronics (VE) and solid-state technologies.

VE RF amplifier technology can provide the performance needed to meet the requirements of many future military systems. VE amplifiers are being developed and used in EA jammers, towed decoys, advanced missile seekers, mobile high-data-rate EHF satellite communications terminals and data links, and communication satellites. These devices are designed to meet the unique system requirements and tailored to provide the maximum performance capability. To meet the needs of the next-generation of military systems, however, S&T investments must be made to develop advanced VE devices and supporting technologies and to maintain the capability of the U.S. industrial base.

DoD investments in VE S&T during the past decade have resulted in dramatic advances in device performance, reliability, and life. The remarkable performance capabilities of modern VE devices are presented in the body of this report. The development of new device concepts, improved component designs, and a computer modeling and simulation environment using advanced tools are the direct result of the Tri-Service/DARPA VE Initiative (1990 to 1995) and the Navy's VE S&T program (1996 to 2000).

Funding cuts threaten to destroy the entire VE S&T program and seriously erode the U.S. technology base. Funding of VE S&T has decreased from $35M (FY01$) in FY93 to $7.7M in FY01. At this level, many ongoing projects have been postponed or eliminated, and there is no funding for U.S. industry development efforts. An even greater threat is the proposed $4.5M Navy budget for VE S&T for FY02. This proposed budget would virtually stop VE technology advances that are needed to meet identified future military system requirements. The capability to trade-off the attributes of VE and solid state technologies is critical to optimizing system designs. The lack of advanced VE device options will create undue high risk for the success of future DoD systems development. Without a viable VE S&T program new engineering talent will be discouraged from entering the field, severely limiting VE R&D capability and putting the long-term viability of the industrial base at risk.

In response to this critical situation, AGED Working Group A conducted a Special Technology Area Review of Vacuum Electronics in December 2000. The goal of this STAR was to determine the current state of the technology, the military requirements for VE devices for current and future systems, and the S&T investments required to meet these needs. Contributors to this STAR included representatives from the military Services, the U.S. VE industry, Government laboratories, and Universities.

Based on the findings of this STAR, AGED Working Group A has developed recommendations for S&T investments in Vacuum Electronics.

$5M per year funding for Basic Research (6.1) including the MURI program.

$12M per year funding of Applied Research (6.2) to continue and expand current development of advanced VE technologies.

$10M per year funding for Advanced Development (6.3) to transition new VE devices to production readiness.

$5M to $7M ManTech total funding for 3 years to mature Microwave Power Module designs, and reduce production cost.

$3M per year continued funding for Title III Supplier Chain Improvements for VE production.

$2M to $4M per system for upgrades to fielded VE based RF transmitters to enhance performance and reduce O&M costs.

PRINCIPAL FINDINGS

Progress in Vacuum Electronics

1. VE technology is continuing to achieve significant advances in performance and reliability, particularly in the areas of high RF power at millimeter-wave frequencies, ultra-broad bandwidth, reliability, and linearity with high efficiency. These improvements are shown in Figures A through E (following the Findings). Since 1980, performance advances that have been achieved are:

    - Average RF power has increased by a factor of 10 at 40 GHz and by a factor of 50 at 100 GHz.

    - Bandwidth (Fmax/Fmin) has improved by 2 times to more than 3 octaves

    - Efficiency (Pout(RF)/Pin(DC)) has increased to 73% for narrow-band devices and 50% for broadband devices.

    - Reliability has increased by 10 to 100 times for military and space applications. Current space TWTs are achieving in-orbit MTTF of greater than 10 million hours.

2. The dramatic performance advances of VE devices are being accelerated by the development and use of advanced 2D and 3D modeling and simulation codes. These codes provide accurate performance predictions from physical dimensions and material characteristics, allow design optimization without experimental iteration, and result in "first-pass design success." This capability also reduces cost, development time, and program risk.

Satisfying Future System Needs

3. VE technology is essential for new EA systems to meet the combined performance requirements of high power (100 to 300 W), ultra-broad bandwidth (2 to 3 octaves), high efficiency (>30%), and small size.

4. VE technology provides short-pulse high-peak-power (1 kW to 100 MW) needed for radar, HPM, and high-energy accelerator applications. The short-pulse high-peak-power capability of VE devices provides not only improved radar performance but also high energy-per-pulse for HPM weapons.

5. The use of VE amplifiers (such as MPMs) to provide the transmitter power for phased arrays, combined with advances in signal processing and solid-state receive modules, can be a viable alternative to solid-state TR modules for Active Electronic Scanned Array (AESA) radar dependent on system architecture. MPMs are being considered for fully populated AESAs at frequencies below 12 GHz (where antenna element spacing is compatible with the cross-section dimensions of the vacuum power booster), and may be an ideal match when the aperture size is limited. Alternately, each MPM can drive subarrays of radiating elements. Future improvements to low-loss system components (circulators, phase shifters) can significantly increase the efficiency and RF power of systems using MPMs. Owing to their newness, reliability and cost barriers to MPM use in systems must be overcome with additional investments in producibility to mature their designs, demonstrate reliability, and reduce the production cost.

6. Microwave Power Module technology is being used by the DoD and foreign military community for miniaturized transmitter applications. Ultra wide-band (3 to 18 GHz) MPMs that provide RF

output power of >125 watts average power and efficiency of 35% have been developed for Electronic Attack (EA) applications. This technology is also being used for towed decoy applications. Narrow-band (4 to 6 GHz) MPMs have achieved greater than 200 watts average power with greater than 50% efficiency and 10 dB noise figure in a package size of 49 cu in. Their small size, high efficiency, and medium-to-high RF power capability makes MPM technology ideal for communication transmitters for small platforms such as UAVs, mobile satellite communication terminals, and Future Combat Systems. MPMs are also being used for distributed and modular EA transmitter architectures. MPMs located near the radiating elements provide increased radiated RF power (due to lower losses) with less prime power and cooling.

7. VE amplifiers are used on nearly all communication satellites owing to their high efficiency, long life, and exceptional reliability. Space Traveling Wave Tube Amplifiers (TWTAs) routinely achieve efficiencies of more than 70%, lifetimes of greater than 18 years, and MTTFs of more than 10 million hours. Space TWTAs have higher in-orbit reliability than comparable space solid-state power amplifiers. Significant improvements in the reliability of VE amplifiers in military systems can be achieved through careful control of design tradeoffs and transmitter interfaces similar to commercial space TWTAs.

8. VE is the only technology currently available to meet military system needs for medium-to-high RF power (>50 watts) at millimeter-wave frequencies (i.e., above 30 GHz). System requirements for RF output powers of 50 watts to 100 kilowatts at frequencies from 30 GHz to 130 GHz have been identified for radar, EA, towed decoys, and communication satellites as well as ground terminals. VE devices are being increasingly used in military communication terminals including SMART-T and Submarine HDR systems. Medium-to-high power (between 80 and 160 W) at millimeter-wave frequencies (44 GHz to 60 GHz) with high efficiency is required to achieve high-data-rate capability and reliable satellite links.

9. Future radar, EA, communication, and multi-function systems will need power amplifiers with high linearity and high efficiency for operation with advanced signal processing. High linearity TWTAs with C/3IM of –50 dB to – 60 dB and efficiency of 40% have been developed at 2 GHz for commercial communications by using linearizers combined with multi-stage depressed collectors (see Figure E). Additional development is needed to extend these technologies to meet military network-centric requirements.

10. A recent comparison of life-cycle cost between two Navy radars, one based on vacuum electronic amplifiers and the other an all solid-state system, show that the initial acquisition cost and annual cost-of-operation for the transmission function are roughly comparable.

11. Development of Multiple Beam Klystrons (MBKs) may provide compact low-noise (–140dBc/Hz at 4kHz offset) transmitters for radar, missile seekers, and space applications. Advantages of MBKs include wide bandwidth (10 to 20%), high efficiency (>30%), dramatically lower noise, and operating voltage equivalent to comparable power crossed field amplifiers (CFAs). This technology has been developed and used in Russian radar and communication systems. The development of multi-beam amplifier technology will require the use of advanced 2D and 3D computer modeling and simulation codes.

New Systems

12. There are a number of new DoD systems that may use advanced VE devices. Among these are:

    - PAC-3 missile seeker
    - Firefinder Block II AN/TPQ-47
    - HDR submarine satcom terminal
    - SMART-T and other advanced EHF satcom terminals
    - SIRFC AN/ALQ-211 airborne EA jammer
    - Towed decoys for F-15, F-16, F-18, B-1
    - EA transmitters for F-15, F-16, F-18, UAVs, EA-6B
    - AN/TPS-75 Ground Theater Air Control radar
    - Predator UAV SAR and satcom data link
    - Global Hawk avionics
    - Multi-Role Radar

    These new applications require continued funding of VE Applied Research, Advanced Development, and ManTech to achieve system performance and cost goals. These new military system applications provide important markets needed to maintain a strong U.S. VE industry beyond 2050.

Current System Needs

13. There are currently 272 fielded military systems using 185,000 VE devices. These systems are used in many military weapons platforms, including:
    - Fighter aircraft (F-14, F-15, F-16, F-18)
    - Bombers (B-52, B-1B, B-2)
    - Ships (Destroyers, Cruisers, Carriers, Submarines)
    - UAVs (Predator, Global Hawk)
    - Radar (AWACS, JSTARS, Firefinder, PATRIOT)

    These systems will continue to be in use for at least 20 to 30 more years. The number of VE devices in use will increase to more than 190,000 over the next 5 years due to planned new system deployment. In 2030, 80% of current fielded VE systems will still be in use and will require replacement spares or upgrades (see Finding #11). Advanced VE devices (new designs and technologies) being developed to support new military systems (see Finding #12) will add to these numbers.

14. Most fielded DoD systems use VE devices that were developed 15 to 30 years ago, before the availability of modern simulation and modeling codes and design tools. The cost of updating transmitters with modern VE, which provides improved performance and reliability, is a much lower investment cost than redesigning the systems for alternative technology approaches. An ongoing example of this approach is the AEGIS SPY-1 Radar and Mk 99 Illuminator systems. Over the past 16 years, the operating cost per hour of the VE amplifiers was reduced by a factor of 23. DoD funding in this area could realize a high return-on-investment.

Device Requirements

15. The development of cathode materials that operate at lower temperatures (down to room temperature) could significantly increase life, reliability, efficiency, and performance of VE devices and transmitters. Feasibility has been demonstrated using a field emitter array cathode on a C-band helix TWT.

16. Advanced materials and fabrication processes are needed to meet future system requirements for power and efficiency at millimeter-wave frequencies. These include dielectric materials (such as diamond and aluminum nitride) with low loss and high thermal conductivity and lossy dielectrics based on aluminum nitride for internal attenuators and RF loads.

17. Additional investments in supporting technologies will enable addition improvements in VE-based system performance. Development of low-loss low-cost phase shifters with power handling capability of greater than 10 watts per element will increase the RF output power and efficiency of corporate and distributed-feed array systems. Future improvements in solid state driver amplifiers, high voltage diodes, switching devices and circulators will further increase MPM performance and efficiency and reduce their size and weight. Additional development of MPM power conditioner technology is needed to improve reliability, cost, and producability.

Technology and Industrial Base

18. A significant industry concern is the erosion of technical knowledge and experience within DoD and OEMs with regard to the current and future performance capabilities of modern VE devices. As a result, DoD system trade studies may not thoroughly capture the performance, cost, and risk advantages offered by VE technology.

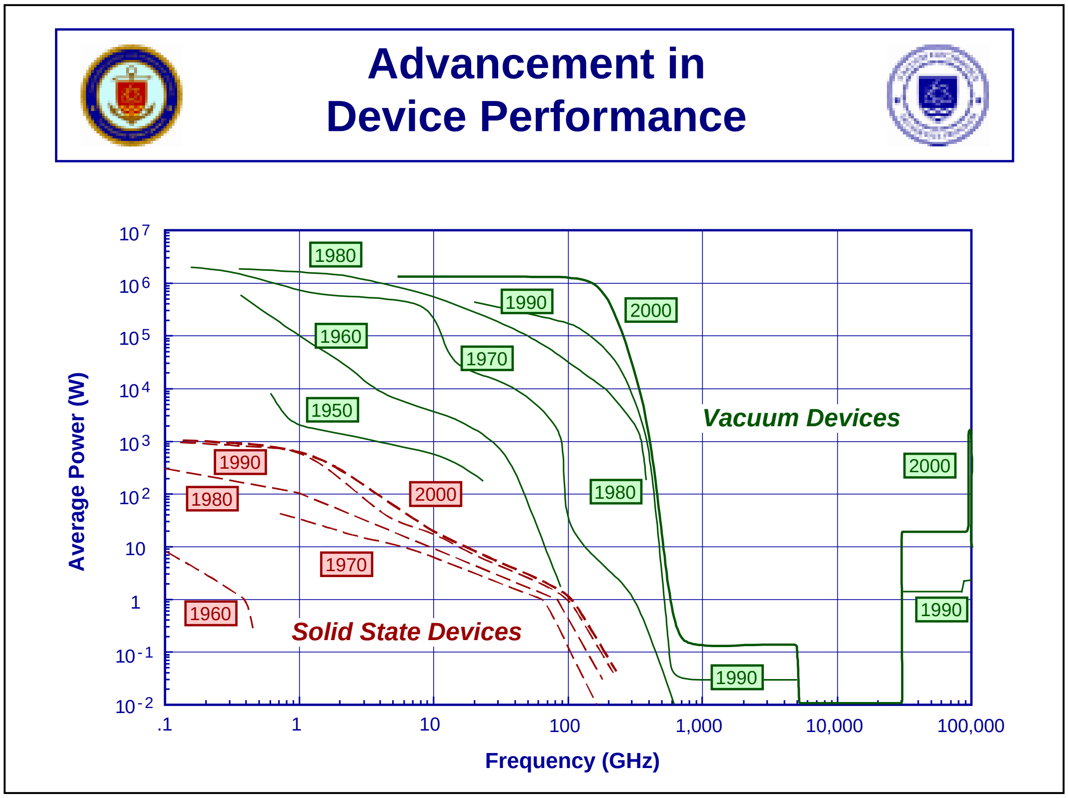
19. As a result of a limited commercial market, the low volume of VE production does not support multiple sub-tier suppliers of specialized components. The industry relies on a limited supplier base for components such as helix tape, lossy beryllia ceramics, heater filaments, cathode assemblies and rare earth permanent magnets. The performance and quality of these components are strong drivers of the end product performance, manufacturing yield and cost of VE devices. A Title III VE supplier base program base been initiated to develop improved manufacturing and business processes at key suppliers. Funding for the FY01 Title III program is $3M.

20. DoD procurement is, and will be continue to be, greater than 75 percent of the total US VE market. Limited industry IR&D is being invested in developing devices for potential high-growth commercial markets. This makes advances in VE technology needed for military systems highly dependent on DoD investments in VE S&T.

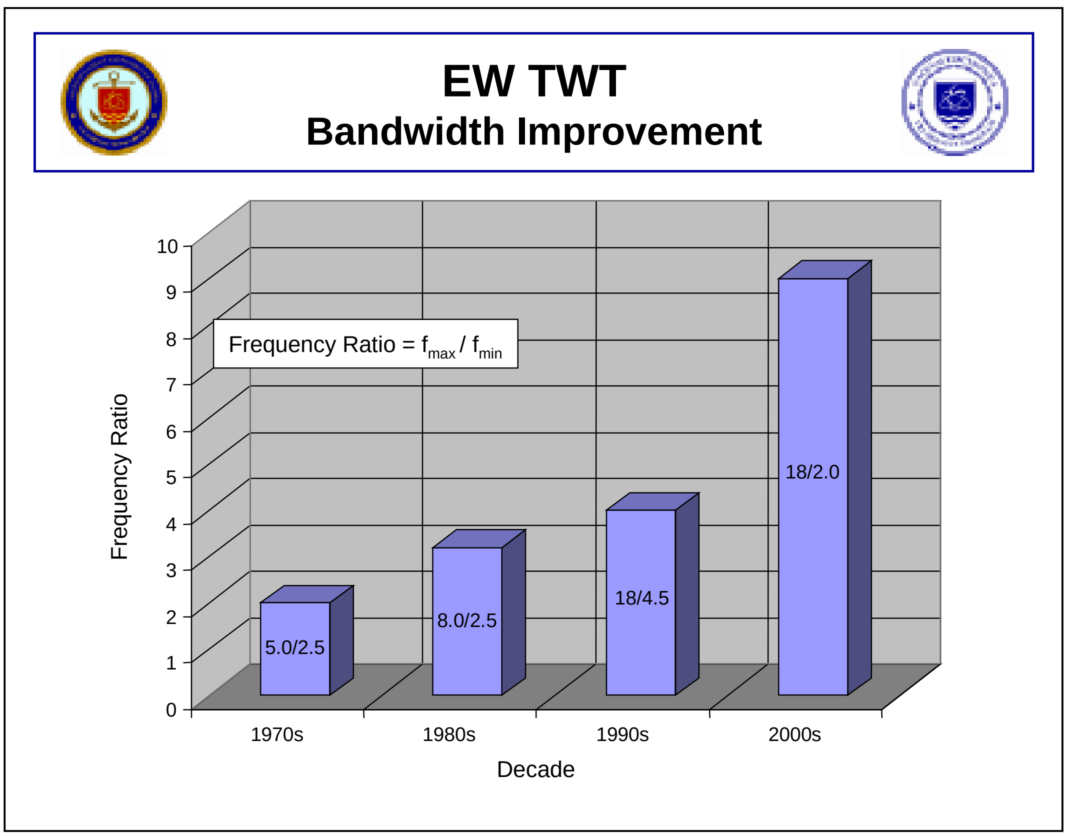
Funding

21. The Navy is the primary source of DoD Science and Technology (S&T) funding for VE, a result of Project Reliance supported by PBD-208 that increased the Navy's TOA. (Funding of $12.6 M (FY01$) in FY88 was considered seriously inadequate when OUSD(A)/DDRE established and funded the Tri-Service Vacuum Electronics Initiative.) VE S&T funding has decreased from $35 M (FY01$) in FY1993 to $7.7 M in FY 2001. This level of funding threatens to destroy the entire VE S&T program. At the current level, there is no funding to support S&T projects in the manufacturing industry.

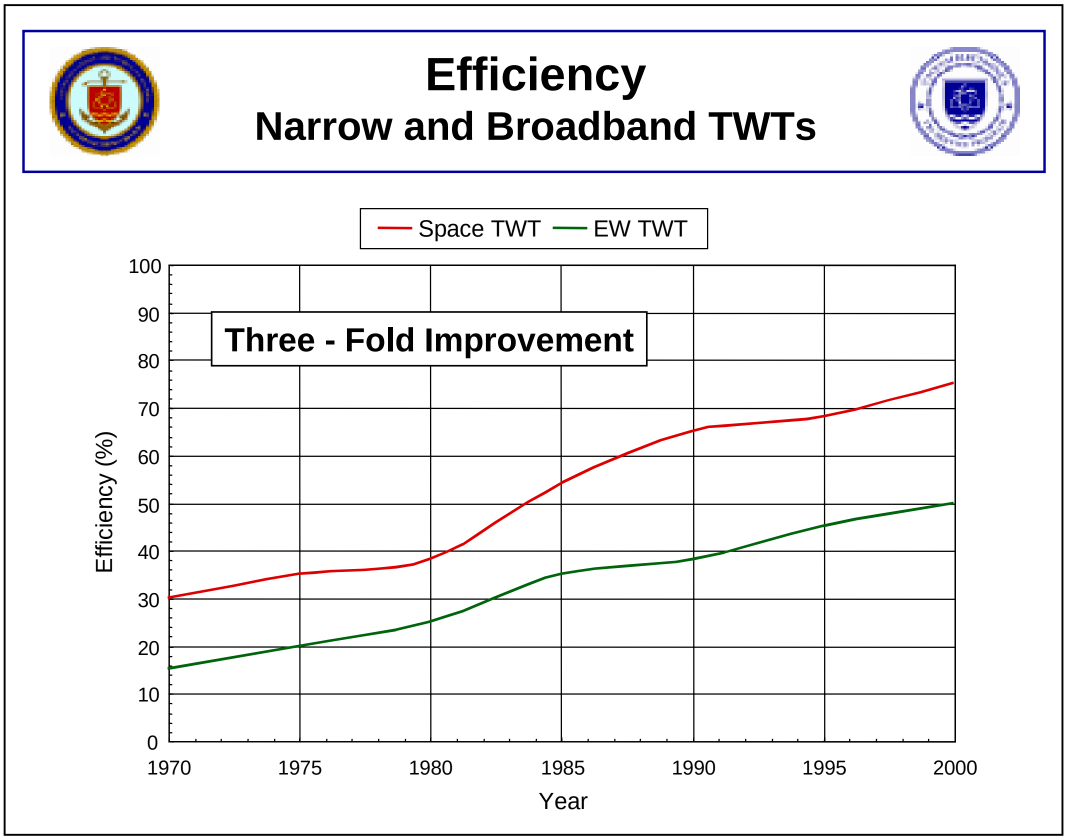
22. University research in VE technology is resulting in development of exciting microwave and millimeter-wave devices and improved understanding of basic beam-wave interaction physics, multi-tone amplification, intermodulation, and noise. Universities are making rapid advances in novel vacuum electron devices (gyrotrons, Klystrinos, etc.), new microfabrication techniques (LIGA), novel cathodes (carbon nanotubes and silicon tip emitters), new ceramic materials, and innovative computational techniques. There is strong coupling with industry and Government laboratories and collaboration within the University community. The Microwave Vacuum Electronics MURI 99 supports VE research and graduate studies in six major universities. Long term stability of funding is a concern. Universities are the primary sources of engineers and scientists for the U.S. VE industry. There is a continuous demand for trained graduates to sustain the industry's technical capability. Stable, long-term funding of VE research is needed to strengthen current programs and attract faculty and students.



(Figure A)



(Figure B)



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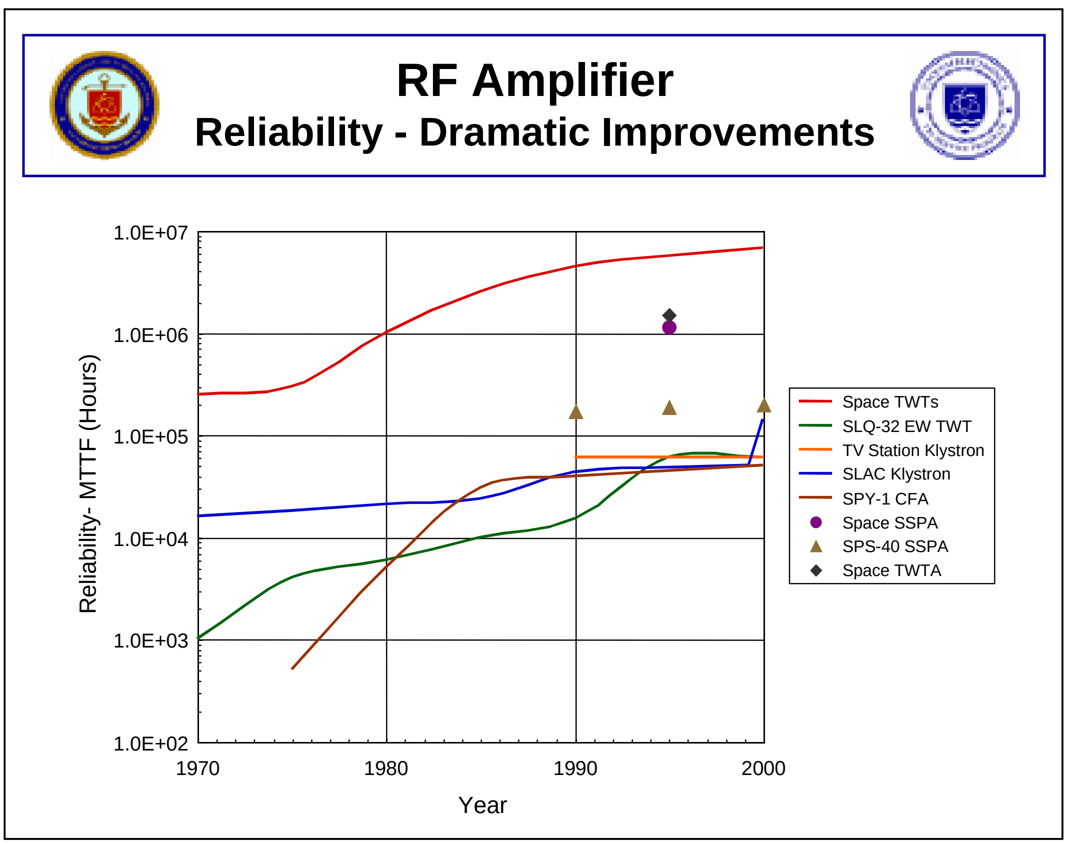

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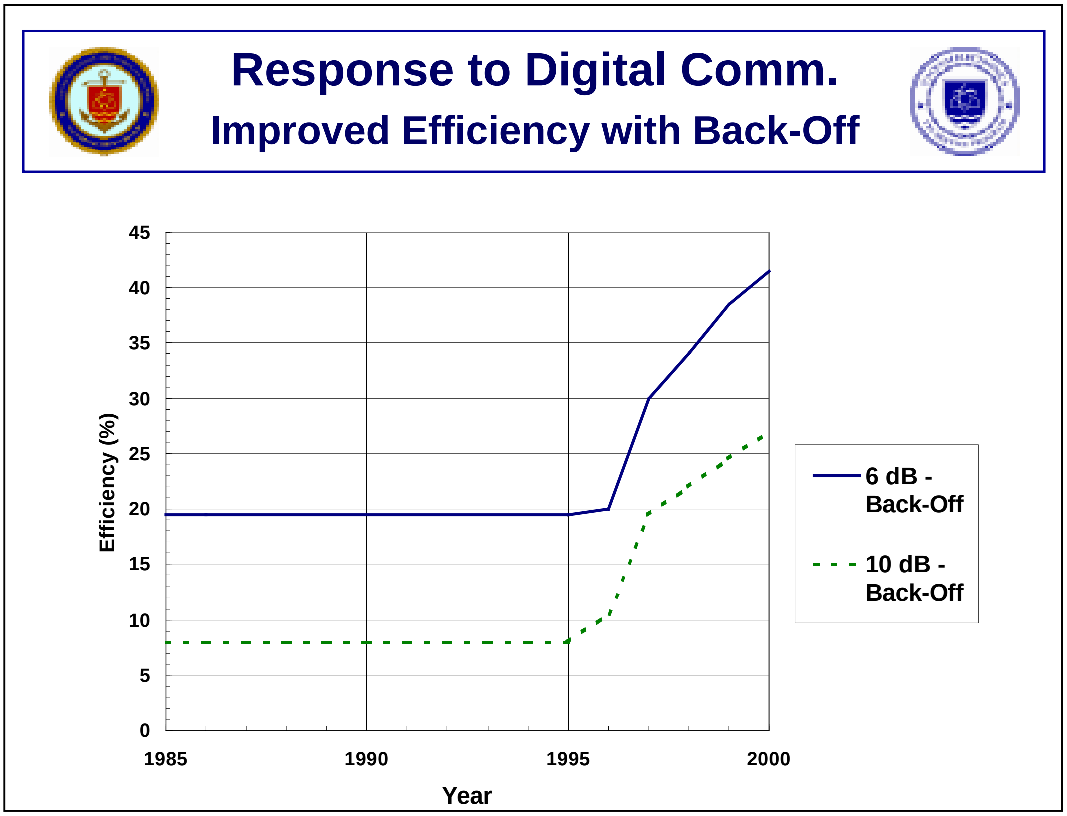

Response to Digital Comm.
Improved Efficiency with Back-Off
Efficiency (%)
45
40
35
30
25
20
15
10
5
0
1985
1990
1995
2000
Year
6 dB - Back-Off
10 dB - Back-Off

(Figure E)

CONCLUSIONS AND RECOMMENDATIONS

I. APPLIED RESEARCH

RECOMMENDATIONS

To ensure that that high performance VE devices required for new military systems will be available when needed, restore VE S&T Applied Research (6.2) funding to $12M per year for at least 5 years. This funding is also necessary to sustain the U.S. industrial base R&D capability.

To support future systems needs, specific VE (6.2) Applied Research funding is required in the following areas:

1. Continued development of accurate numerically-efficient 2D and 3D modeling and simulation codes, which are essential for all aspects of research, development, and manufacture, to achieve the required performance and reduce development, acquisition, and life-cycle costs.

2. Development of specific VE device types for identified and potential system insertion opportunities including:

   - Ultra-wide-band helix TWTs and Vacuum Power Boosters (low-gain helix TWTs) with increased RF power for EA applications and towed decoys.

   - Slow-wave millimeter-wave helix and coupled-cavity TWTs and Extended Interaction Klystrons with higher RF power, greater bandwidth, and higher efficiency for high-data-rate communications, missile seekers, and UAV-based synthetic aperture radar.

   - High-power millimeter-wave gyro-amplifiers for high-resolution radar.

   - High-power S-band multiple beam klystrons with low phase noise to provide an amplifier option for the AN/SPY-1 to transition into the NTW Block II Backfit program.

3. Development of advanced sub-component technologies including high-power RF circuits, application of new dielectric materials, improved electron emitters, high-efficiency multi-stage depressed collectors, and high-perveance electron guns with precision optics.

II. ADVANCED DEVELOPMENT

RECOMMENDATIONS

There is currently no funding for Advanced Development efforts to transition advanced VE RF amplifiers to system insertion readiness. Advanced Development (6.3) funding of $10M per year is needed to refine and mature these VE designs, develop robust assembly processes, and address environmental and reliability requirements. These efforts are key to reducing the cost and risk of system development.

These VE applied research and advanced development programs should be directed by a Tri-Service steering committee and conducted as a unified DoD program. This is the same program

management approach that was used successfully in the previous Tri-Service/DARPA Vacuum Electronics S&T Program.

III. BASIC RESEARCH

RECOMMENDATIONS

Increase Basic Research (6.1) funding to $5M per year for 5 years to strengthen university programs in VE research and education including MURI and competitive individual basic research projects.

IV. LEGACY SYSTEMS

RECOMMENDATIONS

DoD funding of $2M to $4M per system is needed to modernize and upgrade existing systems that use VE devices. This approach will provide enhanced system performance and reliability at a much lower investment than completely redesigning the systems for alternative technologies. It will also result in significant operating cost savings over the remaining system life (20 or more years).

V. MPM ManTech

RECOMMENDATIONS

ManTech funding is required to mature MPM designs for specific targeted systems (EW, towed decoys, and mobile communications). These efforts will include design for manufacturing and pilot production needed to mature the technology, develop low cost manufacturing processes, and demonstrate reliability and life. The estimated level of funding required is $5M to $7M over 3 years. Areas that must be addressed include the vacuum power booster TWT, the electronic power conditioner, the solid-state RF driver amplifier and MPM packaging and test.

VI. INDUSTRIAL INFRASTRUCTURE

RECOMMENDATIONS

The recommended level of funding is $3M per year for 5 years to provide additional Title III funding. This funding is needed to address supply chain issues for critical materials and components for VE devices. The improvements achieved with this program can significantly improve the performance and manufacturing cost of VE devices, resulting in a high return on investment.

APPENDIX A: AGENDA
11-12 December 2000

Monday, December 11, 2000

Introduction (8:30am – 9:30am)

8:30am – 9:00am	Summary of DoD systems using Vacuum Electronics Devices (L Vanzant)
9:00am – 9:30am	U.S Industry Overview & Trends (J Christensen)

University Presentations (9:30am – 11:00am)

9:30am – 10:00am	University VE Programs Overview (N Luhmann)
10:00am – 10:30am	University VE Theoretical Programs (T Antonsen)
10:30am – 11:00am	University VE Experimental Programs (R Temkin)

BREAK (11:00am – 11:15am)

Application Presentations, Part I (11:15am – 4:00pm)
Note: Northrop Grumman presentations were given 2:00pm – 3:15pm due to scheduling issues.

11:15pm – 11:45pm	NAVSEA and NAVAIR programs (J Dutkowski)
11:45pm – 12:15pm	Army Programs (R Del Rosario)
12:15pm – 12:45pm	Air Force Programs (R Worley)

LUNCH (12:45pm to 1:30pm)

1:30pm – 2:00pm	SLAC and DOE Programs (G Caryotakis)
2:00pm – 2:30pm	EW System Applications (Towed Decoys, MPM, etc) – Northrop Grumman (R Langietti - Northrop Grumman)
2:30pm – 3:15pm	EW Device Technology (Towed Decoys, MPM, etc) – Northrop Grumman (R Langietti - Northrop Grumman)

BREAK (3:15pm – 3:30pm)

3:30pm – 4:00pm	HPM Programs **(Classified)** (K Hackett)

Tuesday, December 12, 2000

Application Presentations, Part II (8:30am – 10:00am)

8:30am – 9:00am	NASA Space Programs (E Wintucky)
9:00am – 9:30am	TPQ-47 (J Guild-Raytheon)
9:30am – 10:00am	VE Approaches to Phased Array Systems, Active and Passive Apertures (J.P. Letellier)

BREAK (10:00am – 10:15am)

VE Technology Presentations (10:15am – 1:30pm)

10:15am – 10:45am	Results of S&T Workshop – Comparison of VE and Solid State Capabilities (R Parker)
10:45am – 11:15pm	NRL VE S&T Programs (R Parker)
11:15am – 11:45am	VE Modeling and Simulation Code Development (B Levush)

LUNCH (11:45 – 12:30)

Industry Presentations (12:30pm – 2:45pm)

12:30pm – 1:15pm	Litton (C Armstrong)
1:15pm – 2:00pm	CPII (A Staprans)
2:00pm – 2:45pm	Boeing EDD (J Dayton)

AGED-Only Wrap-up and Discussion (2:45pm – TBD)

APPENDIX B: TERMS OF REFERENCE

PRIMARY OBJECTIVE:

The objective of this STAR is to provide information to aid DoD agencies in planning future investments in the development of Vacuum Electronic devices, and associated technologies, materials and system applications.

SUPPORTING OBJECTIVES:

1. Evaluate the present status and performance advances over the last five years in Vacuum Electronics technologies that are applicable to DoD systems applications.
2. Define the current and future DoD systems RF requirements that are addressed by Vacuum Electronics technologies.
3. Project future device performance capabilities to meet the DoD system RF requirements. Compare the current and future device capabilities with competing solid state technologies.
4. Identify the current technical barriers and advancement opportunities in Vacuum Electronics technologies to address DoD systems requirements.
5. Address the application of Vacuum Electronics technology to meet the performance goals of phased array systems, both passive and active aperture.
6. Identify supporting component and subsystem technologies and advances in those technologies that will enhance the performance of Vacuum Electronics based DoD systems.
7. Assess the current investments in Vacuum Electronics technologies in terms of supporting current and future DoD systems requirements.
8. Assess the need and impact of future DoD investment in Vacuum Electronics technologies to sustain an effective U.S. Vacuum Electronics Industrial Base and University based research program.
9. Develop an investment strategy and detailed roadmap for Vacuum Electronics and supporting technologies for DoD RF applications to ensure meeting current and future system needs and to maximize return on investment.

DEFINITIONS:

Technologies: For the purposes of this STAR, Vacuum Electronic RF devices include: Traveling wave tubes (all types), Crossed field devices, Klystrons, Fast wave devices, High pulsed power devices, Microwave Power Modules (MPMs), Millimeter wave Vacuum Electronic devices, other novel Vacuum Electronic devices.

Materials: Vacuum Electronics materials include: Electron emitters, dielectrics, magnetic materials, coatings, lossy ceramics, etc.

Supporting technologies: These are technologies necessary for the design, modeling and characterization, fabrication, analysis, packaging and testing of Vacuum Electronic devices. Also included are other subsystems and components needed for the application of Vacuum Electronic devices in systems, such as power supplies, phase shifters, linearizers, circulators and other novel components and subsystems.

Applications: Vacuum Electronics technologies include devices and subsystems that produce RF output at frequencies from 0.5 GHz and higher. The RF systems and subsystems that use Vacuum

Electronic devices include surface, air and space based sensors for communications, radar, intelligence, surveillance, reconnaissance, electronic warfare, electronic countermeasures and high RF power weapons.

Technical Barriers: Technical barriers are conflicts between fundamental physical and engineering constraints and the functional requirements needed to use Vacuum Electronics devices in a DoD application. An example of a technical barrier is the conflict between the need for high RF power generation at millimeter wave frequencies and the limitations on prime power and volume. This barrier results in the need to develop compact, high efficiency devices. This, in turn requires the further advancement of low loss interaction structures and electron optics systems.

QUESTIONS TO BE ADDRESSED AT THE STAR:

1. What are the RF applications and systems that will benefit from advances in Vacuum Electronic technologies? What are the status and prospects of early insertion efforts? What is the impact if technology efforts are successful?

2. What are the RF technical barriers best addressed by Vacuum Electronic technologies? What are the technology advancement needs and opportunities? Can the barriers and S&T needs be prioritized with respect to return on investment?

3. What are the recommended technology advancement thrusts and the proper mix of 6.1, 6.2 and 6.3 funding? What is the appropriate mix of S&T efforts in new device concepts, device development, performance modeling and simulation, computer design code development, advanced materials and emitters, basic studies of noise and non-linear effects, etc.

4. What are the system architectures that benefit most from Vacuum Electronics technologies? What are the advantages of these system approaches? What are the supporting component technologies (phase shifters, power supplies, etc.) that should be supported by S&T funds?

5. What are the cost drivers for Vacuum Electronic devices and system applications. What S&T efforts could reduce the cost of development and system operation?

6. What DoD issues can be addressed with the proper leveraging of commercial investments? What commercial investments are being made in Vacuum Electronic technologies? What are the commercial systems applications being addressed? How do the commercial S&T efforts relate to DoD needs?

7. What are the current investments and to what degree do the investments meet the needs of DoD systems applications of the three services? What additional S&T efforts and funding is needed?

8. What is the need and impact of an ongoing DoD S&T investment in Vacuum Electronics technology to sustain an effective U.S. Vacuum Electronics Industrial Base and University Research Program?

APPENDIX C: PRESENTATION SUMMARIES – GOVERNMENT & ACADEMIA

Leonard Vanzant – NAVSEA Crane

Mr. Vanzant provided a detailed summary of DoD systems that use Vacuum Electronic Devices. There are 272 fielded military systems employing 186,000 VE devices. These systems will continue to be in service for the next 30 years or more. The number of operating VE devices will increase to 190,500 by the year 2005. Assuming the most conservative of projections (i.e., no new systems using VE), there will still be, by the year 2030, 145,000 VE devices in use in these current legacy systems, approximately 80% of the present number.

It is generally not economically feasible to replace VE devices in these systems with solid state devices. Such a modification also requires redesign of other system elements and interfaces (cooling, antenna, software, controls, etc.) or a total system redesign and replacement. The investment payback is not attractive due to the total cost of the engineering development, qualification, documentation, production, integration and logistics support.

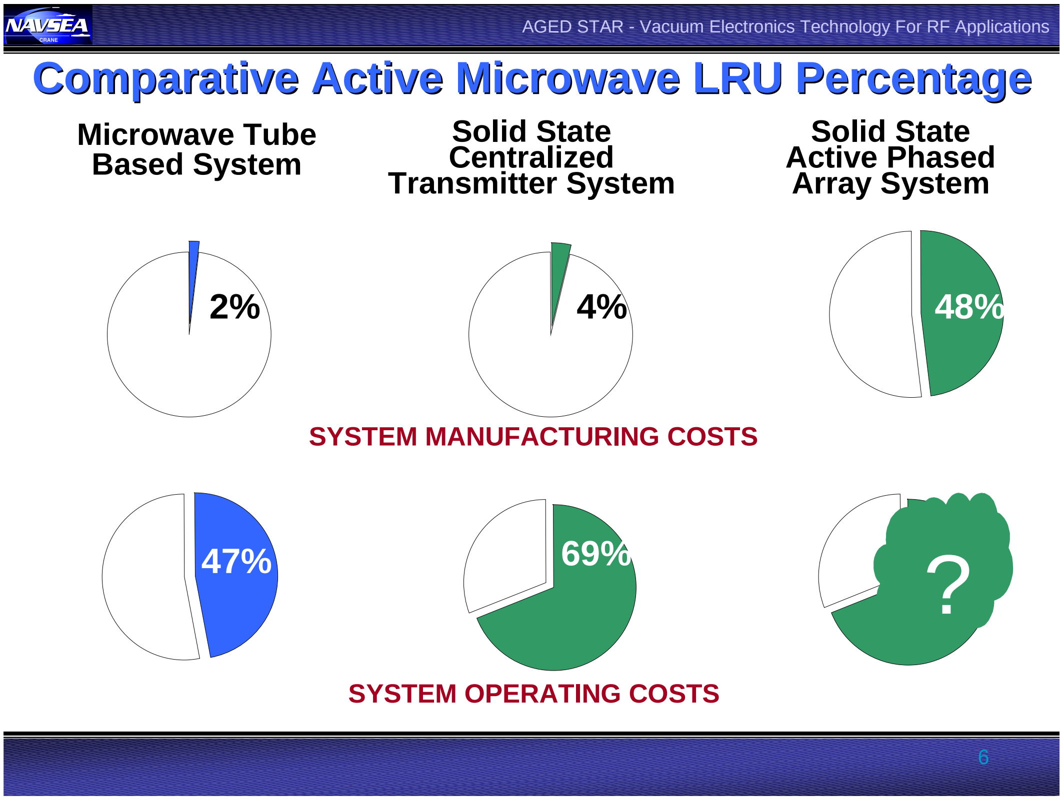
All four military services and NASA have systems that use VE technology. Of the total number of VE devices, 55% are Navy, 33% are Air Force, 11% are Army, and 1% are Marine applications. These systems comprise a broad range of applications:

- Airborne Radar
- Airborne Electronic Warfare
- Missile Seekers
- Surface Radar (Ground and Naval)
- SARs and Data links for UAVs and Simulators
- Communications Terminals

Several new systems are being developed that are using VE devices. These include:

- ALE-50 Towed Decoy
- HDR Submarine Satcom Terminal
- SMART-T Mobile Satcom Terminal
- AN/ALQ-21 SIRFC Integrated EW
- TPQ-47 Firefinder Block II Radar
- PAC-3 Missile Seeker

When applying RF devices to meet system requirements, the importance of Technology Maturity Level and the stress imposed by the Device to System interface is illustrated by the pie charts in Figure 1.



Comparison of microwave tube and solid state transmitter acquisition and operating costs as a percent of total system costs
(Figure 1)

The AN/SPY-1 and SPS-40E radars deployed by the Surface Navy have a centralized transmitter amplifier proving microwave power to the radar antenna(s). While the AN/SPY-1 radar uses vacuum electronic devices as the microwave amplifiers, the SPS-40E utilizes solid state amplifiers. For the AN/SPY-1 radar, the VE devices are 2% of the radar's acquisition cost while the solid state amplifier Line Replacement Units (LRUs) of the SPS-40E are 4% of the radar's acquisition cost.

When the operational cost for the supporting the deployed systems are similarly evaluated, the VE devices for the AN/SPY-1 radar are 47% of the yearly operational support cost while the solid state LRUs for the SPS-40E are 69%.

The importance of achieving a technology maturity level with a stable device design and utilized with a good design margin in the device to system interface is shown by the pie charts for the solid state active phased array. As system operational requirements dictate the utilization of an active phased array system, the amplifier LRUs dominate the acquisition cost (currently around 50% for solid state designs) while the operational support costs are yet to be demonstrated.

Operational experience with microwave transmitters in the working environment is the ultimate measure of actual cost. The many-year experience of the Naval Sea System Command in monitoring and assessing the acquisition and operations cost of surface radar systems provides an excellent background from which insight into the actual total cost-of-ownership for vacuum and solid-state based transmitters can be drawn. For this comparison, the initial acquisition and annual

cost of operation for the vacuum-based AN/SPY-1 and the solid-state version of the AN/SPS-40 were examined. The AN/SPS-40 was selected for this comparison because it is the only solid-state radar with significant operational exposure at-sea. Costs were allocated to the line-replaceable amplifier components of the two transmitters with the intent to compare analogous elements. For the AN/SPY-1, these included all of the vacuum devices, amplifiers (TWTs and CFAs) and switch tubes in the transmitter power chain. In the AN/SPS-40, the solid-state Line Replacement Unit (LRU) is the more easily identifiable element. Given the large cost differential between these systems, transmitter cost was normalized by the total system cost and portrayed as the ratio of Line Replacement unit (LRU) cost to total system cost.

In sharp contrast to the common perception, the normalized cost, initial acquisition, and operations of the vacuum and solid-state LRUs were shown to favor vacuum technology. More specifically, the normalized acquisition cost for the SPY-1 LRU was 2% while that of the SPS-40 was 4%. The corresponding annual cost-of-operation ratios were 47% and 49%, respectively. Although generalization of these results must be done with great care, they do serve to highlight the need for more careful consideration of operational experience in future system decisions.

Mr. Vanzant then provided detailed breakdown of the VE based systems being used by the Army, Air Force, Navy and Marines. This included projections of the VE devices needed for operations support through 2030.

Mr. Vanzant concluded his talk with the following observations:

- VE will continue to be a vital device technology for military systems.
- A wide variety of military systems will depend on VE technology for at least the next three decades.
- Historically, fielded systems are in service longer than initially planned.
- New VE based military systems will be developed that will require performance beyond the current state-of-the art.

Mr. Rick Worley – Air Force Research Laboratory, RF Components

The Air Force has more than 142 fielded electronic systems that use 46,750 VE devices. These RF transmitters operate in specific frequency bands from 100 MHz up to 100 GHz. System applications include communications (ground, aircraft and satellite), radar (surveillance, detection, tracking and fire control), missile guidance (air-to-air and air-to-ground), and electronic countermeasures (self-protect, decoys, standoff jammers). These systems are used on a wide variety of platforms including unmanned aerial vehicles (Predator), fighters (F-15, F-16), bombers (B-1B, B-2), advanced warning aircraft (AWACS), missiles (AMRAAM) and ground (Ground Theater Air Control). Air Force systems using VE will continue to be in use for another 20 to 40 years.

Air Force VE transmitter development emphasis is focussed on UAV and Space applications where prime power is limited and the need for high efficiency is paramount. The key requirements for these systems are moderate RF power, broad bandwidth, small size and weight, high reliability and affordability. VE technologies, especially MPMs, are being developed to meet these needs.

Mr. Worley described a number of VE efforts, previously conducted through the Navy S&T program, that support future Air Force systems needs. MPM developments support the Predator SAR/Satcom systems, Fiber-Optic Towed Decoy (FOTD), millimeter-wave countermeasures, self-

protect and standoff jammer applications, high-data-rate EHF communications, and CDL [Common Data Link] (X-band). Computer design and simulation codes enable performance improvements in wide bandwidth cluster cavity klystrons, multi-beam klystrons and coupled cavity TWTs for AWACS, TPS-75, F-15 and F-16 radars and weapons control systems. Millimeter wave (Ka through W band) VE devices with higher power and greater linearity are needed for EW and HDR communication applications.

Most Air Force basic research (6.1) for VE is funded by AFOSR. The applied research (6.2) level efforts are dependent on the Navy S&T program. Some limited advanced development efforts are funded by AFRL/SNZW and AF project offices.

Mr. Worley presented a series of VE technology development programs that are enabling new system designs, upgrades or advanced capability:

- The Solid State Electron Emitter (SSEM) using InP/CdS/LaS material could provide an "instant on" high current density emission (10 –100 A/cm2) with low voltage modulation (<20 V) for all types of VE devices. Successful development of the SSEM would eliminate the need for heater power and may provide long life and high reliability.
- A fault tolerant transmitter comprised of power combined 6 kW ring-bar TWTs in an MPM architecture has been developed to replace a single high power, high voltage klystron transmitter in the Ground Theater Air Control AN/TPS-75. The low noise characteristics of the MPMs will improve the ability to detect small and conventional targets in the presence of strong ground clutter and ECM.
- A modern wide band klystron has been developed to replace two narrow band klystrons to upgrade the AWACS radar. This has lowered production cost, and improved system reliability and mission availability by providing a hot spare.

The Predator UAV radar was made possible by the MPM development thrust of the earlier Tri-Service/DARPA VE initiative. The availability of modules, even though not fully mature and production ready, saved 3 years of system development time. The high efficiency of the MPM allowed maximum use of the limited prime power for radar range and target detection. The Ku-band MPM technology further enabled a high-data-rate Satcom data link to be incorporated in the UAV.

The MPM's small size and reduced packaging is being used to enhance airborne EW jammer capability, using power combining and distributed transmitter architectures. MPM technology is providing towed decoys with superior RF power compared to the available 3 watt MMIC.

The Navy and Air Force have performed an Analysis of Alternatives (AOA) for the Joint Service Support Jammer (JSSJ) resulting in a technology development roadmap with flight test demonstrations in FY06. The JSSJ system will provide greatly enhanced jamming effectiveness and much higher ERP and is to be compatible with aircraft ECM pods and UAVs. Competing concepts for a JSSJ demonstration include wide band (2 to 18 GHz) MPMs (Northrop Grumman) and a high power solid state MMIC array (ITT). Issues of the maturity of the components, system performance and affordability will be addressed during the program.

VE remains a critical and vital technology to meet Air Force current and future needs. The Air Force is reliant on continued Navy funding for VE S&T.

Mr. Romeo del Rosario – Army Research Laboratory, Army Vacuum Electronics Systems

The Army has a number of fielded systems that employ VE devices. These include artillery and mortar detection radar (AN/TPQ-36 and –37 Firefinder), air defense radar (AN/MPQ-64 Sentinel), electronic warfare systems (AN/ALQ-211 SIRFC), missile seekers (PAC-I, -II, -III), and missile defense radars (Patriot and Patriot Upgrade).

Future Army systems and system upgrades will also use VE RF amplifiers. These include AN/TPQ-47 Firefinder upgrade, the AN/MPQ-64 Sentinel mobile phased array radar upgrade, Multi-Mission radar, SMART-T Satcom ground terminal, TESAR synthetic aperture radar for the UAV, and the SIRFC electronic countermeasures system upgrade.

The AN/TPQ-47 is an upgrade of the Firefinder tactical radar to provide greater detection range and accuracy, higher reliability and greater system mobility. The major RF transmitter requirements for this system are high power and efficiency, small size and weight, and affordable cost. The system design approach selected for the TPQ-47 is a hybrid phased array using multiple, high efficiency, air cooled VE based Power Amplifier Modules (PAMs). The PAMs were selected over competing solid state RF amplifiers using SiC devices, based on higher output power and efficiency and design maturity. The modern designs used in the PAM's TWT also provide a 2 to 4 times improvement in MTBF over the previous Firefinder TWTs.

The AN/MPQ-64 Sentinel radar is also being upgraded. The current implementation plan is to use a higher power transmitter using power combined TWTs or MPMs is being considered to increase the radar range and target tracking.

The SMART-T is a mobile ground terminal for EHF satellite communications. VE and millimeter-wave power modules (MMPMs) are replacing GaAs pHEMT amplifiers to provide the increased power (> 50 W) and lower bit error rate needed for high-data-rate MILSTAR operation. The MMPM's 30% efficiency with higher RF power makes optimum use of the limited prime power available. The cost goal for production quantities of MMPMs is <$25K. Advanced development and ManTech funding is needed to mature the MMPM design and manufacturing processes to meet this goal. The future requirements for even higher data rate capabilities for communication ground terminals will require MMPMs with even higher RF power (>100 W) and increased linearity.

The development of the UAV Tactical Engagement Synthetic Aperture Radar (TESAR) was a major demonstration of MPM capability. Early MPM models met initial Ku-band transmitter requirements, and the system was successfully deployed in Kosovo. Upgraded power and reliability and lower production cost are goals for the next generation UAV.

The Army's Future Combat System (FCS) is currently in the definition stage. The FCS implementation requires multifunctional transmitter capability, robust use of EW and ECM and high levels of communication and platform connectivity. The use of robotics and lightweight vehicles places a premium on obtaining the highest transmitter RF power and efficiency and the smallest size. Mr. del Rosario stated that VE and MPM technologies are viable and attractive candidates to meet these requirements.

The ALQ-211 SIRFC is an integrated Electronics Countermeasures system to protect helicopters. The current system architecture uses a broadband TWT transmitter. An upgrade of the system using MPMs will improve jamming performance and reduce size and weight. The smaller

MPM package permits mounting near the antenna, reducing RF losses and increasing transmitted power.

The Patriot PAC-III and Medium Extended Range Defense System (MEADS) missile seeker uses a Ka-band coupled cavity TWT that is currently produced by Thales in France. VE is the only RF technology that can meet the combined requirements for high peak and average power at Ka-band within the small available volume. CPI is qualifying a competing design under ManTech funding to provide a domestic production source.

Mr. del Rosario described the Army's Multi-Function RF Sensor Technology development effort. The goal of this program is to develop small, lightweight, multi-function system technologies that support Target Acquisition, Combat ID, Weapons guidance, Secure communications and EW protection. A demonstration of multi-function capability with a single 35 GHz antenna is planned by FY03. The current approach is an active array using a Rotman lens and 2-W solid state TR modules at each port. Micro-TWTs and MMPMs, which have inherently more bandwidth, power, and efficiency could provide a long-term upgrade path.

The Army funding of VE R&D for FY00 and FY01 is $300K per year for ARL internal efforts and $150K per year for contracts. The contract funding is projected to decrease to $50K for FY02. The Army relies on the Navy VE S&T program to support the needs of the Services. The current levels of funding are not sufficient to meet the Army's future system needs for advanced VE devices.

Mr. del Rosario summarized the Army's present and future VE needs as follows:

- Continued VE capability is imperative.
- Electronic Countermeasures require MPMs and MMPMs for upgrades and new systems.
- MPM cost must be reduced below $25K for Satcom terminals.
- Cost, reliability and performance are major determinants for future Army applications.
- MPM and MMPM technologies are viable candidates for the Future Combat System.
- Increased funding of the Tri-Service VE program at NRL is necessary for Army VE programs.

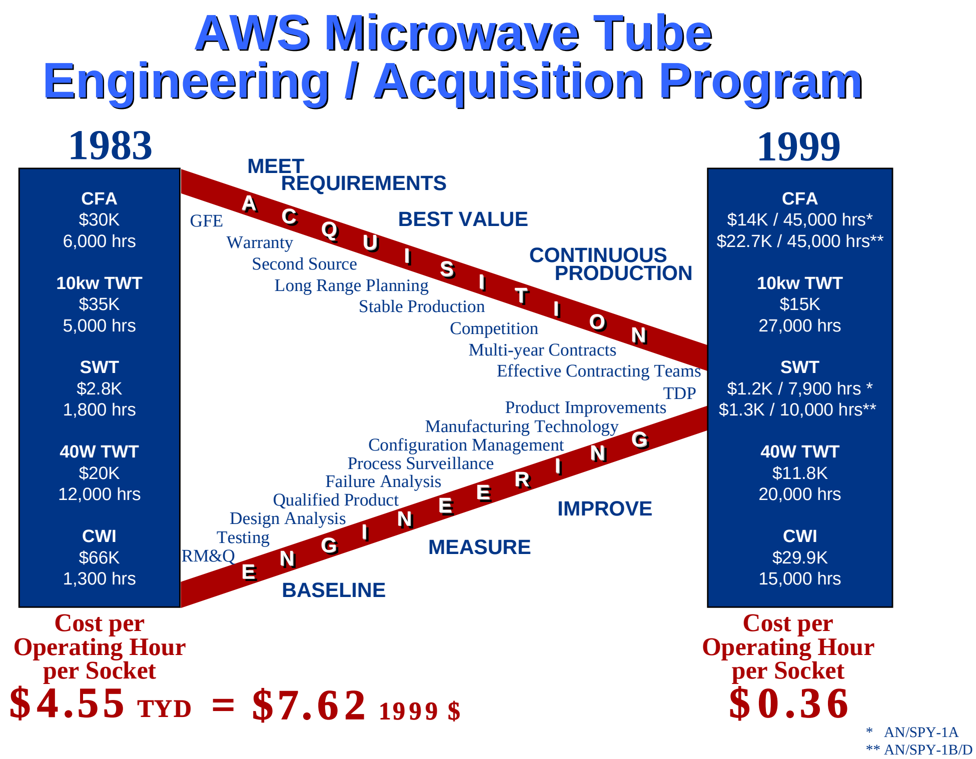
Mr. Joe Dutkowski, NSWC Crane

Mr. Dutkowski presented the issues and opportunities for improving the reliability of fielded systems using VE devices. NSWC Crane is involved in the testing and maintenance of many Navy and Air Force systems representing 47% of the VE devices in use by the military. This experience has provided insight into the issues that determine the reliability of VE transmitters and the approaches for significant improvements.

The reliability of VE devices in fielded military systems is primarily driven by:

- VE device design
- VE manufacturing processes
- System interfaces and environments

By addressing these issues using modern VE design and manufacturing techniques, the reliability of VE transmitters can be greatly improved. For the AEGIS SPY-1A and SPY-1B systems, the operating life of the CFAs was increased from 6,000 hours to 45,000 hours and the cost was reduced from $30K to $14K. The life of the Coupled Cavity Continuous Wave Illuminator (CWI) TWT was increased from 1,300 hours to 15,000 hours, and the cost was reduced from $66K to less than $30K. The cost per operating hour for the total system was reduced from $4.55 ($7.62 per hour in 1999 dollars) in 1983 to $0.36 in 1999. The dramatic cost and reliability improvements of the VE devices used in AEGIS system are shown in Figure 2 below.



Cost and Reliability Improvements of VE Devices Used in AEGIS System
(Figure 2)

The primary design issues that contribute to reduced reliability and life are:

- Transmitter designed for maximum performance, without considering reliability
- Insufficient VE design margins
- Antiquated 1960-1970 design technology
- Inadequate power supply regulation and protection circuits in the transmitter

In evaluating the origin of failure of VE device, the electron gun has been found to be the biggest contributor to failures. The use of the advanced modeling and simulation codes and improved materials (cathodes, RF windows, magnets) to upgrade old VE designs can provide greater performance margin and more robust, repeatable designs. Upgrading the power supply designs to address interface problems will also increase the performance and reliability of the VE devices, resulting in significant reductions in system operating and maintenance costs.

In addressing the manufacturing issues that influence reliability, a program conducted at Crane concluded that increased emphasis on processing, beam-focusing and testing of VE devices during manufacturing will result in increased reliability. The marginal cost for these efforts will be much less than the resulting operational cost savings. Mr. Dutkowski recommended funding of ManTech programs to develop improved brazing, metalizing and electron gun assembly processes.

Mr. Dutkowski observed that there is a critical need for DoD investment in VE Advanced Development (6.3B and 6.4) and ManTech (7.8) in order to provide reliable, cost effective products for new and existing military systems. For example, SPS-48, 49, APG-65/73 and APS-116 are possible candidates for (and would benefit from) 6.3 and 6.4-level investments to improve reliability and make more affordable. In addition, ALE-50, ALE-55, ALQ-184 and SLQ-32 systems would benefit from ManTech investments for mini-TWT manufacturing.

Mr. Dutkowski presented the following conclusions and recommendations:
There are opportunities for large improvements in fielded system reliability and operational cost savings by upgrading VE device and transmitter designs using current design technologies. These improvements can be achieved at an affordable cost.
OSD needs a balanced investment for VE:

- Funding for S&T to improve design and material technologies
- Funding for Product upgrades and Manufacturing Process improvements.

Edwin Wintucky, Electron Device Technology Branch, NASA Glen Research Center (GRC)

The NASA Space Based High Rate Data Distribution (HRDD) Program[1] is currently defining a new space communications network, the Space Internet, to provide the communications services needed to satisfy the greatly increased high data transmission rates (up to 10 Gbps) of future Earth Science Enterprise (ESE), Space Science Enterprise (SSE) and Human Exploration for Development of Space (HEDS) missions. NASA is projecting a 10 to 1000 times growth in data rates in the next 20 years. The Space Internet will resemble the terrestrial Internet in its capability to provide end-to-end high-speed information delivery, in this case from the point of scientific data collection to the user on the ground. A number of communications architectures are being investigated to meet the need of the different enterprises for more communications capacity, greater connectivity and much higher data rates. The data requirements of the architecture elements (backbone, access, inter-spacecraft and proximity wireless networks) will determine the new technology and hardware requirements. The Space Internet is a significant departure from past procedure in which the technologies were typically mission specific and thereby limited in application.

Vacuum Electronics is a key technology to meet future NASA communication requirements, particularly in the communication links in the backbone and access networks. Higher data rate communication systems require more RF power at higher frequencies (e.g., Ka and V bands), more bandwidth and greater linearity. For example, space based communication transmitters operating at 32 GHz would require an RF power output of 100 W or more in order to provide 1Megabit per second data rate capability to distant planets. Space applications also place a premium on high efficiency, minimum weight and high reliability. VE technology has demonstrated the ability to meet these requirements.

[1] In FY02, the Space Based HRDD Program becomes the Space Communications Project in the Computer Information Communication Technology (CICT) Program, also in the NASA Aerospace Technology Enterprise.

The Electron Device Technology Branch in the Communications Technology Division at NASA GRC is supporting these system needs by developing VE technologies that will maximize efficiency, bandwidth, lifetime and reliability while minimizing mass and size. Their technical approach is:

- Advance the analytical and optimization capability of the computer codes used for VE device modeling
- Develop computer models to reduce the cost and development time of new VE devices
- Investigate materials and new cathode designs for novel vacuum devices
- Investigate new slow-wave circuit fabrication techniques

Several VE projects are being performed under the current HRDD program, which are directed to meeting the requirements for future NASA communication system architectures:

- The Simulation and Optimization of TWTs project has developed accurate 3-D models of the electron beam/RF interaction and codes for analysis of beam focusing, electron guns and multi-stage depressed collectors. GRC is also developing a time dependent code to analyze and reduce intermodulation distortion in TWTs.
- In the area of RF circuit design, GRC is investigating novel circuits for a > 100 W, 32 GHz TWT.
- A novel, very high gain, ladder-type RF circuit design is being developed that would provide 10 to 20 W RF at 26.5 GHz and 32 GHz with an overall TWT efficiency of 50% to 60%.
- A proposed application for is the RF drive for a ferroelectric shifted, electronically scanned, power efficient reflectarray antenna system under development at GRC.
- Boeing EDD will be developing under contract to NASA a 32 GHz, variable power (30 to 100 W), near constant efficiency (> 50%) for high rate data transmission.

Dr. George Caryotakis, Stanford Linear Accelerator Center (SLAC)

Dr. Caryotakis presented the ongoing Vacuum Electronics research and development efforts at SLAC.

The Stanford Linear Accelerator center (SLAC) is a High-Energy Physics laboratory, operated since 1962 by Stanford University under contract to the Department of Energy. Research at SLAC is conducted, for the most part, by using electron and positron high-energy accelerators, to collide these particles and to convert their annihilation energies into short-lived bosons, quarks and other elemental debris, which are sorted out and studied by huge computerized detectors. The importance of microwave sources (usually klystrons) to power these accelerators is only second to the design and construction of the accelerators themselves, but both accelerators and sources are based on the same principles, first developed at Stanford University in the 1950's. For a measure of this effort on klystron capabilities, see Figure 6. The first multi-megawatt klystron was built at Stanford in 1948 to power the first modern disk-loaded waveguide accelerator, developed in parallel to the klystron.

As a consequence of this general background SLC has continued developing new klystrons for new, increasingly more powerful accelerators and, alone in the world among High Energy Physics laboratories, maintains a well-equipped facility for the engineering and manufacturing of klystrons, accelerators, and other high power microwave components.

A major current program at SLAC is the development of a new collider, designed to attain energies in the 500 GeV to 1 TeV range, and intended to help discover the Higgs boson, whose existence is predicted by theory. This machine, known as the Next Linear Collider (NLC), would be 20 miles long and would employ approximately 4000 X-band klystrons.

The NLC klystron has been under development at SLAC for the last 12 years, at a cumulative cost exceeding $20 million. The size of this effort can be best understood by comparing the desired performance of the device to the state-of-the-art when the project was initiated. The prototype NLC klystron, expected to go on test this spring, will produce 75 megawatts in 3-microsecond pulses, at a repetition rate of 180 Hertz. It will operate at 500 kV and its beam will be Periodic Permanent Magnet (PPM)-focused, in order to reduce the total power consumption of the machine. By replacing the solenoid beam-focusing magnet with a PPM-structure, the power consumption of the solenoid is avoided. In 1990, the power output of commercial pulsed klystrons did not exceed 20 megawatts at S-band (klystrons produced by Thomson, in France), although SLAC manufactured, for its own use, S-band klystrons, at 65 MW. The NLC prototype klystron is being "Designed for Manufacture", since the cost of klystrons in the NLC is a major consideration in the design of the machine.

The technology developed in connection with the NLC klystron has many applications in vacuum electronics devices (VEDs) of importance to the DOD. This was recognized early in the 90's when SLAC, in collaboration with the University of California at Davis became active in two Air Force initiatives, ATRI and MURI. The principal thrust of the research performed under these programs was in Microwave Directed Energy, sometimes referred to as High Power Microwave (HPM). The performance sought for HPM devices and the technical challenges they present are very similar to those of the NLC klystron, for the reasons below:

- HPM requires high peak power, with short pulses, with narrow bandwidth. If it is considered that the maximum power attainable by a VED scales approximately with the wavelength, it can be seen that 75 MW at X-band are comparable to 7.5 Gigawatts at 1000 MHz, where most of the HPM device effort has been concentrated.
- The Pf^2 law applied to higher, rather than lower frequencies, suggests that design techniques used at X-band would be useful at millimeter wavelengths, which are also of importance to Microwave Directed Energy (see Figure 6).
- Experimental HPM devices built at various laboratories in the last 15 years are based on field emission cathodes, which are not compatible with good vacuum. An excellent vacuum is the cornerstone of the NLC klystron devices, because of the RF breakdown (pulse shortening) which invariably occurs at the high electric field gradients necessary in a high peak power source.
- Low-temperature oxide cathode research is important to the NLC, since dispensed cathodes, which operate at very high temperatures, are both expensive and contributors to shorter device life. High current beams are very important to HPM devices and oxide cathodes are capable of high current densities, if properly formulated.

These congruent goals of NLC klystron development and DOD Directed Energy initiatives have been pursued in ATRI-MURI programs during the last 6 years, in the following projects:

- Oxide cathode research
- High gradient RF breakdown research.
- "Klystrino" development.

The oxide cathode research addresses the escalating requirements for higher current density in accelerator sources and DoD applications. The premise of the research is that an oxide cathode fabricated without binders, or the need to decompose the carbonate emission material will have a much higher current density and much more reproducible performance. The elimination of potential poisoning agents should significantly increase cathode performance. SLAC will use laser ablation deposition (LAD) to deposit, on a nickel substrate, the emission materials (barium, strontium, calcium) in metal form in the presence of oxygen.

RF breakdown is a very serious issue in high power tubes and in accelerator structures. SLAC has a large experimental program underway to identify the causes of breakdown in RF structures and to modify, treat, and/or process the components to improve the breakdown threshold. An experimental program to identify the frequency dependence (if any) of RF breakdown is also in progress.

The klystrino is a 100 kW peak power klystron that will operate at W-band. It has a 0.5mm beam in a 0.8mm beam tunnel. In order to succeed with this device significant issues regarding circuit fabrication and beam focusing had to be addressed. The fabrication issue was solved using LIGA (Galvanoformung Abformung), a German lithographic technique that produces structures a few millimeters deep with micron dimensional tolerances. Operating at 110 kV (microperveance of 0.067) makes the use of PPM possible. A six-centimeter long, unshunted PPM beam tester achieved better than 95% transmission. Several klystrinos operated in parallel (or in a phased array) offer the potential of high average power generation at W-band, in small, lightweight packages and at a reasonable voltage.

A total of 6 UCD graduate students (5 Ph.D. candidates, one Master's) have participated in this research. Two in this group are now full-time employees of SLAC.

In addition to the MURI research, a 1-Gigawatt L-band klystron (funded by the Air Force) is being developed at SLAC with collaboration with Los Alamos National Laboratory. The tube employs a magnetron injection gun to produce the required current (4000 amperes). It is expected that, operated at 800 kV in a LANL modulator, this will be the first HPM source to produce 1 gigawatt, with 1-microsecond pulses, and a pulse repetition rate of 5 Hz.

Dr. Neville Luhmann, Jr., University of California, Davis

Dr. Luhmann presented an overview of the Vacuum Electronics education and research programs that are being conducted in universities throughout the United States.

Vacuum electronics research in the university sector is supported by the DOE, NASA, NIH, as well as the DoD. The DoD sponsorship is driven by electronics and directed energy applications. Vacuum electronics research is being conducted in twelve major U.S. universities, including MIT,

Stanford, UC Davis, UC Berkeley, UCLA, University of New Mexico, Texas Tech, University of Maryland, Wisconsin, Northeastern, and Dartmouth. There is good interaction within the university communities and strong coupling with industry and Government laboratories. This research is providing exciting new technologies and innovations. VE research has the opportunity for explosive growth due to advancements in microfabrication and computational techniques.

In the aggregate, the VE programs are staffed by 17 regular faculty, 30 research faculty, and involve 46 faculty in related fields (plasma physics, accelerators, E&M, etc.). There are currently 42 Ph.D. students and 21 M.S. students engaged in VE research. Over the past ten years, 90 Ph.D. and 83 M.S. degrees have been awarded.

DoD funding of VE research at the universities is approximately $3.4 M per year, primary from the Microwave Vacuum Electronics MURI ($1.24 M) and AFOSR ($1.42 M). Annual non-DoD funding is $2.2 M, primarily from DoE. The universities also spend about $7.5 M per year in support, equipment and facilities. Dr. Luhmann expressed concern that the university VE research programs are underfunded and lack continuity.

Dr. Luhmann next described the MURI Microwave Vacuum Electronics (MVE) Research Program, which is being performed by a consortium of six universities (MIT, UC Davis, Stanford, Maryland, Wisconsin and Michigan). This is an integrated, multidisciplinary program doing research in the following areas:

- Novel microwave and millimeter-wave sources.
- Advanced materials and fabrication techniques for VE devices
- Analytic theory and computer simulation
- Innovative distance learning and data archiving
- System design

Examples of microwave source research include microwave tube/solid state hybrid devices, millimeter-wave gyro-amplifiers (140 GHz and 94 GHz), microfabricated millimeter-wave sources and photonic crystal based devices.

Advanced materials and fabrication efforts include carbon nanotube cathodes, photoenhanced field emitter arrays, advanced ceramics and microwave absorbing materials and laser deposited high current density oxide cathodes.

Basic research is being performed in advanced devices physics, multitone amplification, intermodulation and noise, electromagnetic modeling of VE devices, electron spin resonance spectroscopy at 140 to 1000 GHz. This research addresses the requirements for future digital, high-data-rate communication and radar systems.

The microwave education and distance learning involves an extensive graduate curriculum in MVE, video teleconferencing with industry participation, internet-based education, and data archiving. This project is not only educating new engineers and scientists in VE technology, but is also developing methods of archiving the knowledge and experience of experts in the field.

Dr. Luhmann described the extensive University facilities that are required for VE research. These include microwave and millimeter-wave test equipment, high voltage power supplies and

modulators and advanced fabrication equipment. The Universities have made a significant resource commitment to VE technology.

Dr. Luhmann concluded his presentation with the following conclusions and recommendations:

- VE research is in a renaissance period of growth and achievement due to new concepts, advanced microfabrication techniques and theory/computational tools.
- There is strong industry demand for trained graduates in VE.
- Long-term funding continuity is extremely important to ensure that graduate students can complete their degrees. However, VE basic research funding is extremely fragile.
- Increase and stabilize DoD 6.1 funding to $9M to $10M per year.

Dr. Tom Antonsen, University of Maryland

Dr. Antonsen discussed the theoretical Vacuum Electronics research that is being conducted at a number of U.S. Universities. Most of these universities are participants in MURI99 Innovative Microwave Vacuum Electronics Consortium. VE theoretical research is also being carried out at the University of California at Berkeley and the University of California at Los Angeles. There is an extremely close connection between theoretical and experimental efforts; theoretical work is also carried out by experimentalists.

The VE theoretical research is divided into three areas: developing novel devices, understanding and explaining basic phenomena, and developing new modeling and simulation tools. These areas span the range of activities from relatively basic research to highly applied research.

Most of the university effort in developing novel sources has focused on fast wave devices, such as the free electron laser, gyrotron, peniotron. A list of these includes: Fundamental and Harmonic Gyro-TWTs and Penio-amplifiers (UCD, UMD), Confocal Resonator W-band Gyro-TWTs (MIT), Photonic Band Gap Cavity Fast Wave Amplifiers (MIT), Harmonic Multiplying Phigtrons (UMD), and Clustered Cavity Gyro-Klystrons (UMD). In the area of slow wave devices there are efforts in the fabrication of millimeter-wave Klystron arrays (SLAC). Theoretical contributions usually consist of performing analytic calculations of the expected performance of these hypothetical configurations.

Research in understanding basic processes in vacuum electronic devices focuses on both the beam-wave interaction and issues affecting beam quality. Activities include: gain equalization and inter-modulation suppression in TWT amplifiers (UWisc), noise mechanisms in VE devices (UMich, UCB), TWT amplifier physics (MIT, UMD), time frequency analysis of complex signals (UMich), and physical processes in cathodes (UMich). These efforts involve a close connection between theory and experiment. There is also close collaboration of the University groups, industry and the National Laboratories.

Modeling and simulation has become a key enabler in the design and optimization of VE devices. Universities are playing an important role in this effort. University activity in this area includes: development of simulation codes for the modeling of multi-stage fundamental and harmonic Gyro-Klystrons and Gyro-TWTs (UMD), development of self-consistent codes for photonic band gap structures and Gyro-amplifiers (MIT), the development of advanced green's

function simulation tools (MIT), and implementation of PIC simulations of W-band Klystrons (SLAC).

In all the university VE efforts there is close collaboration among academic, national lab and industrial researchers. Examples include the NRL/CPI/Litton/UMD W-band Gyro-Klystron development, the University of Michigan/NRL collaboration on noise, and the University of Wisconsin/ Northrop Grumman collaboration on intermodulation distortion in TWTs. The relatively small size of the VE community places additional demands for archiving and disseminating the VE knowledge base. The demand for textbooks is likely to be small, thus alternative forms of archiving knowledge must be pursued. Also, it is essential for theoreticians to interact with related communities such as plasma physics, accelerator physics, computational electromagnetics and communications.

Universities serve an essential role in educational initiatives involving VE technology. Most important of these is the education and development of the next generation of scientists and engineers who will support the U.S. industrial base. Given the competitive job market for technically trained personnel it is important to attract talented students into the VE field. One of the most effective ways is by offering students exciting university research opportunities.

Dr. Richard Temkin MIT Physics Department and Plasma Science and Fusion Center

The Innovative Vacuum Electronics MURI (Multidisciplinary University Research Initiative) program consists of research on the physics of wave / particle interactions, including microwave generation; electromagnetics, including interaction circuits (slow wave circuits and fast wave circuits), dielectric materials and magnetic systems; physics of beams including cathodes, beam formation, beam transport; and thermal and mechanical engineering including power density limited operation of devices in areas such as cathodes, cavities, windows, beam tunnels, and electromagnets.

Dr. Temkin stated that the primary goals of the experimental program are to:

- Train the next generation of scientists / engineers in our field and,
- Demonstrate advanced vacuum electron devices representing major advances in understanding and performance.

The university VE programs are highly successful in meeting these important goals.

Dr. Temkin reviewed the experimental programs at each of the universities. These programs are strongly interconnected and collaborative. In each case, the overview covers only a small portion of the ongoing university research in Vacuum Electronics.

A Gyro-TWT experiment is under construction using a confocal waveguide circuit. It is based on an existing 140 GHz driver and a new 95 GHz driver. The confocal cavity has the field profile of the HE06 mode in a confocal cavity. Modeling of the open confocal cavity at 140 GHz was carried out using the Ansoft High Frequency Structure Simulator (HFSS) code. In first experiments, a confocal cavity (as opposed to an amplifier) has been investigated. This experiment showed that mode competition had been significantly reduced, a major advance in gyrotron research. This demonstrated the effectiveness of the confocal circuit. In the planned amplifier experiment,

which is under construction, it is expected that a saturated power in excess of 100 kW, efficiency in excess of 25% and a bandwidth in excess of 3% will be achieved.

In research on a novel Photonic Bandgap (PBG) structure, a TM01–like operating mode has been studied at 17.1 GHz in theory and in cold test. The cavity mode is created by a defect mode (missing rods) in a triangular array of metal rods. Modeling of the cavity has been done with HFSS and theoretical results agree well with cold test experiments. Advantages of the PBG structure include:

- oversized structure (ease of fabrication and suitable for high frequency),
- higher order mode discrimination,
- ease of coupling into the PBG cavity (distributed coupling with small frequency shift), and
- possible MVE (microwave vacuum electron) applications such as input/output couplers and interaction circuits. Future plans are to use such a structure in an active MVE device, such as a gyrotron or klystron.

A program of research is also being conducted on novel cathodes. Research includes work on high aspect ratio field emission arrays with tips made of silicon and an effort on carbon nanotubes.

The Stanford research program is conducted at the Stanford Linear Accelerator (SLAC), which has world class fabrication facilities. Research is aimed at demonstrating a 95 GHz klystron based on novel fabrication techniques. The device is referred to as a klystrino. The structure will be made by LIGA. The process consists of lithography through a mask and electroplating followed by removal of a PMMA layer. It promises to allow high quality, high precision fabrication of the small, deep structures needed for a klystron at a frequency of 95 GHz. An experimental device is being fabricated.

The University of California program includes research on a 94 GHz TE01 Gyro-TWT Amplifier. The objectives are to extend TWT technology into the millimeter range and to develop a stable W-band 100 kW gyro-TWT amplifier. The approach is to use Gyro-TWTs which offer wide bandwidth, to use the TE01 mode to transmit high power, to loss stabilize the amplifier and to use stability codes to determine needed loss. At present, the 94 GHz gyro-TWT is being assembled; the circuit has been fabricated; the MIG gun has been built; input and output couplers have been tested and large-signal codes predict an efficiency of 28%. The University of California is also building a 91 GHz Sixth-Harmonic Gyrotron, a Ka-Band Second-Harmonic Peniotron, and a Second-Harmonic Gyro-TWT Amplifier.

The University of California also conducts research on Quasi-Optical Grid Array Sources. Solid State–MVE Hybrid devices and configurations are attractive. The combination of novel layered semiconductor device structures and photonic crystals, together with the newly developed microwave/millimeter-wave power module (MPM/MMPM) promises revolutionary, compact high power sources in the 30-300 GHz region for next generation DoD systems. Research is also conducted on Gated Silicon Field Emission Array Photocathodes. Advantages include: Field emission does not require a heating filament, optical gating avoids capacitive effects associated with electrical gating, prebunching capability reduces microwave circuitry and shortens tube length, shorter tube length requires fewer magnets for beam confinement, and shorter tube length also increases efficiency.

The University of Maryland program is investigating a Ka-Band, frequency – doubling harmonic Gyro-TWT. The experimental parameters are: Voltage 40-70 kV; Current 8-35A; Input 16-18 GHz; Input Power 100 W; Gun Field 1.1 kG and Main Field 6.6 kG. The device has produced over 100 kW of output power in the 32 to 34 GHz frequency range. There is also an effort on microwave sintering of high performance ceramics for microwave tubes. Major achievements include: high thermal conductivity; controlled losses; good mechanical properties; near net shape and simultaneous multiple sample processing and thermal and dielectric characterization capabilities.

This research program is aimed at understanding noise in DoD microwave tubes and exploring noise reduction techniques. The scientific/technical approaches are: theory (both analytic and computational techniques and experiment) and signal spectra by time-frequency-analysis. Accomplishments so far include a breakthrough in klystron intermodulation theory; flicker noise analysis and time-frequency-analysis on magnetron signals.

A key research activity is the development of a wideband TWT research device. This is being done in collaboration with Northrop Grumman research group. The objective is to improve the understanding of the fundamental physics of nonlinear TWT operation including multicarrier and complex time-domain signal amplification. The NRL code Christine will be very helpful in this research.

A second research activity is nonlinear multitone dynamics in klystron amplifiers (KLAs). This is a collaboration with University of Michigan (UM= theory; UW=experiments). It will improve fundamental understanding of multitone nonlinearities in linear-beam vacuum electron devices and identify intermod suppression methods for multitoned KLAs.

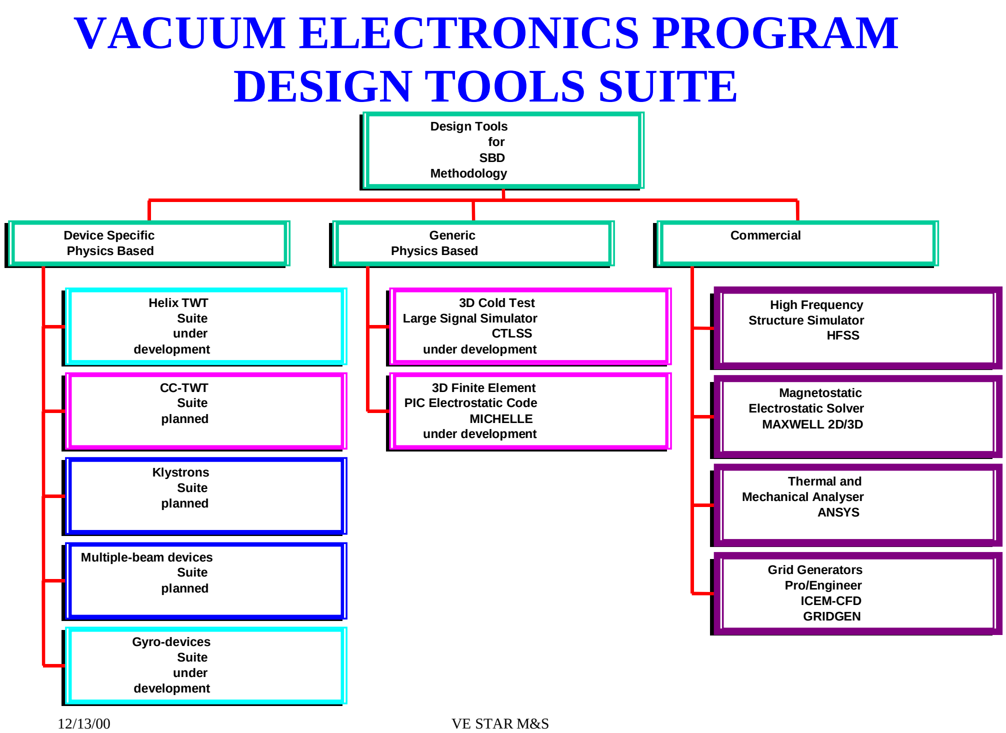


Figure 3

Vacuum Electronics Experimental Research is making fundamental advances in the four key research areas: Physics of Wave / Particle Interaction; Electromagnetics; Physics of Beams; and Thermal and Mechanical Engineering. A strong graduate education program is a major part of the program. Important collaborations have been developed between universities, national labs and industry. Future plans for this research area include many novel ideas which will lead to evolutionary and revolutionary advances in VE technology and device performance.

Dr. Baruch Levush, Naval Research Laboratory

Dr. Levush heads the Vacuum Electronics Modeling and Simulation Code project at NRL that is developing the suite of computer design tools shown in figure 3 below.

(Figure 3)

The computer design tool suite is made up of three types of codes:

- Commercial codes including High Frequency Structure Solver (HFSS), Magnetostatic Electrostatic Solver (MAXWELL 2D/3D), Thermal and Mechanical Analyzer (ANSYS), and Grid Generators (Pro/Engineer, ICEM-CFD, GRIDGEN).

- Generic VE beam/RF interaction physics codes: 3D Cold Test and Large Signal Simulator (CTLSS) and 3D Finite Element PIC Electrostatic Code (MICHELLE).

- VE device specific physics codes for Helix and Coupled Cavity TWTs, Klystrons, Gyro-devices and Multiple-beam devices. These would include multi-frequency large signal analysis, stability analysis, cold test codes with lossy materials and complex geometry, gridded electron gun simulations, beam focusing analysis and multistage depressed collector simulations including secondary and elastically scattered primary electrons.

The goal of the NRL program is to develop accurate and efficient VE design tools with predictive capabilities operating on desktop computers. Some of the principles that are being followed in the development of these codes areas follows:

- The design tools should be capable of finding the optimum performance by varying parameters.
- The design tools should be able to model the actual geometry and material properties of devices.
- Accuracy versus efficiency (iteration speed) trade-off must be made.
- Solutions must be accurate enough to be meaningful.
- Dependence on “code gurus” should be minimized.

These codes are in various stages of development. Several of these codes are already in use throughout the industry and are enabling significant VE device performance improvements, reduced development time, and first pass design success. The VE industry has formed a Modeling and Simulation advisory group to provide inputs on specific needs and to share code validation and usage information. Dr. Levush presented some impressive examples of the successful application of these codes to current VE development programs.

The development and enhancement of a complete suite of VE design codes is a technical challenge that will require continued funding for many years. Recommended S&T funding for this program is $4M per year.

The resources and funding for training, support and maintenance of these design codes are issues that need to be addressed by both DoD and the VE industry.

J.P. Letellier, Naval Research Laboratory, Radar Division

Mr. J.P. Letellier discussed radar phased array architectures in general, and the system performance tradeoffs between solid state and Vacuum Electronic devices used in phased array transmitters. He also addressed some specific issues related to possible upgrade of the Navy's Aegis SPY-1 radar.

Mr. Letellier showed a variety of feed structures for phased array antennas that can utilize VE devices. These include constrained (corporate) feeds, both serial and parallel, and space (optical) feeds. Some series corporate feed antennas actually take advantage of the element spacing to steer to a given angle for a given frequency.

Mr. Letellier next discussed the issue of phase noise, which has been widely quoted as a reason for replacing the VE devices in the current SPY-1 radar with an all-solid state transmitter. The present SPY-1 transmitter combines the output of 32 tubes, and provides a roll-off of –55 dBC/MHz. Mr. Letellier stated that combining 10,000 solid state sources will result in <u>much higher</u> phase noise.

Mr. Letellier pointed out that near term advances in signal processing will significantly reduce the doppler spreading effect of the phase noise of the transmitter. Because of the stability of presently available local oscillators and the bandwidth/bit-width of present or very near term A/D converters, it is possible to sample and store samples of the outgoing signal as a template against which return signals can be filtered. This will allow the system to turn the normal doppler spread on the outgoing signal and the return clutter signal into a sharp frequency spike at zero instead of obscuring the near zero doppler ranges. Thus, transmitter phase noise is not an important discriminator in the tradeoff of VE versus solid state phased array transmitters.

A third issue in VE versus solid state amplifiers in phased array radar arises from the fact that in the present Aegis radar, the receiver and transmitter elements are separated from the antenna elements by the distribution network. It is widely accepted that the receive losses in the network degrade the available signal to noise ratio by about 12 dB. These losses could be nearly eliminated by locating the LNA, phase shifter with receiver protection and circulator close to the antenna elements. It is not necessary to require the transmitter RF devices (VE or solid state) to be located at each antenna element.

Thus, it should be possible to achieve significant SPY-1 performance improvements without having to resort to a solid state WBG transmitter array. The selection of the RF power amplifier technology should be a matter of cost tradeoffs.

Short pulse, high peak power capability is important for shipboard radar transmitters. Since both the radar and the potential targets are moving in unpredictable ways, it is advantageous to use

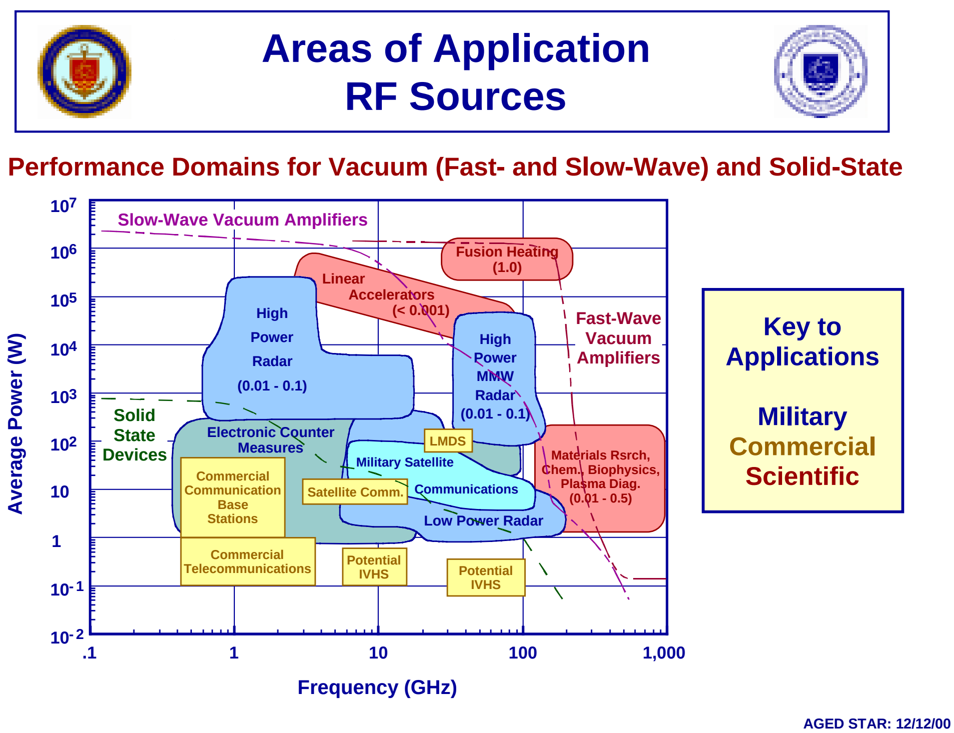
short pulses in order to not "smear" the signal returns. A short pulse is preferred for any radar that is using a common antenna to transmit and receive, in order to decrease the time that the receiver is blanked by the transmit pulse. For instance, if the transmitter is on for 30% of the time, only 70% of the time is available to receive return signals. Even more important, the part of the time that the receiver is blanked off is the area closest to the ship. For example, a 24 microsecond pulse will blank the first mile around the ship, and a 480 microsecond pulse will blank the first 20 miles.

Vacuum Electronic RF amplifiers provide greater short pulse capability than solid state, due to the higher (orders of magnitude) peak RF power.

Dr. Robert Parker – Naval Research Laboratory, Vacuum Electronics Branch

Dr. Parker presented the VE research efforts at the Naval Research Laboratory (NRL). NRL's Vacuum Electronics Branch conducts R&D programs in RF Vacuum Electronics technologies and administers and manages contracted R&D programs with industry and Universities. NRL is the lead service for VE R&D under Defense Reliance and is the primary DoD laboratory for this technology.

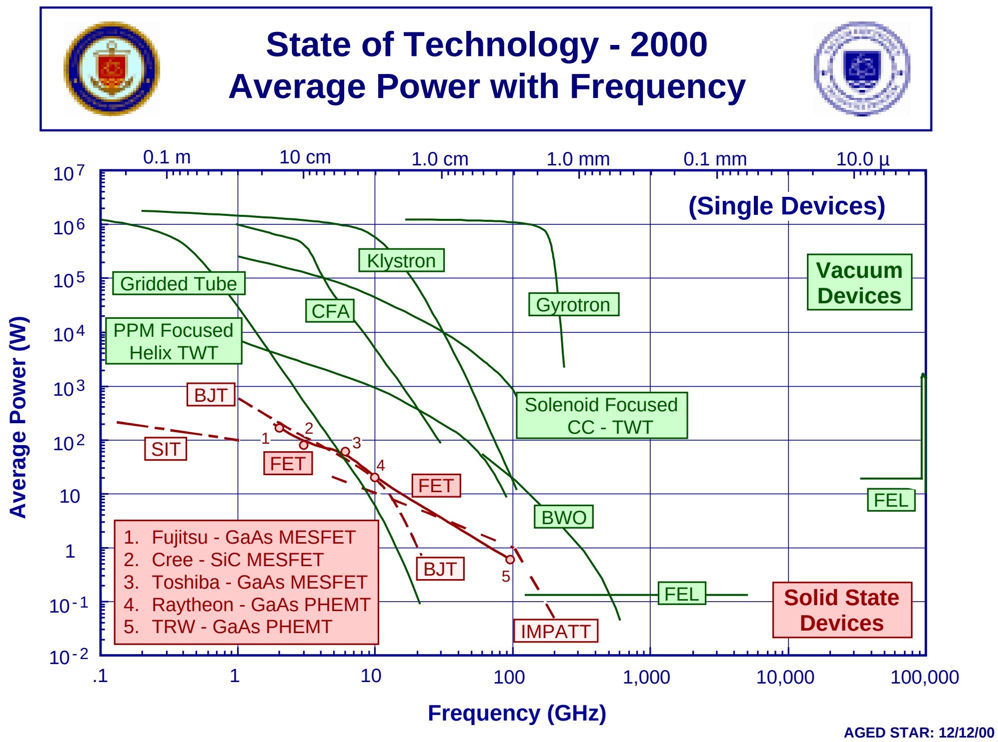
Dr. Parker showed the general power/frequency requirements for military systems and the current performance capability of single solid state and VE RF power devices. This is shown in Figure 4.



Power-Frequency Domains for Military Systems Compared With the High-Power Envelope of Single RF Devices
(Figure 4)

To meet some of the high power and high frequency system requirements using solid state power amplifiers or transmit/receive modules, many devices must be power combined. In contrast, vacuum electronic based systems use either a single high power device or combined lower power devices such as MPMs.

Next Dr. Parker compared the current state of VE and solid state device performance in terms of average power and frequency, shown in Figure 5. This chart includes the current performance limits of the major classes of devices. Dramatic advances in VE device performance and capability have been achieved during the past decade. These advances are due to a combination of device innovation, improved modeling and design tools, the introduction of new materials and component designs and construction techniques.

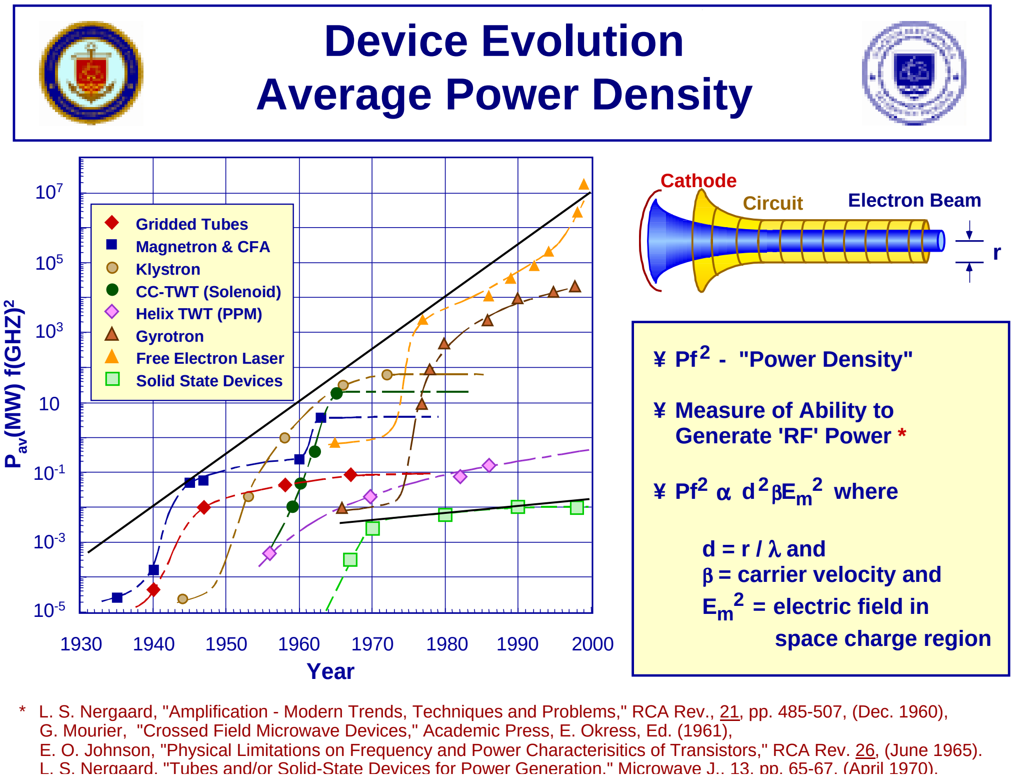


Present State of RF Device Technology
(Figure 5)

The evolution of RF power amplifier technology, both VE and solid state, is depicted in Figure 6 showing average power capability versus frequency at decade intervals from 1950 to the present. The rapid advances achieved in VE are evident in the large increases in average power particularly at frequencies above 10 GHz. Contributing to this trend was the development of new device types such as the Gyro-oscillators and Gyro- amplifiers. Using the figure of merit $P_{ave}F^2$,a measure of the average power density through the transport medium, the performance of VE devices continues to double every two years, much faster than the rate of doubling every 15 years exhibited by solid state technology.

Dr. Parker next discussed the continuing advances in VE device performance and the benefits to DoD applications.

VE devices provide power conversion efficiencies (DC to RF) that can be more than two times greater than comparable solid state RF amplifiers. The efficiency advantages of VE increase at frequencies above 20 GHz. Vacuum, when compared with wide bandgap semiconductors, provides essentially 'collisionless' transport. In addition, the use of multi-stage depressed collectors allows the recovery of up to 85% of the spent beam energy, i.e., beam energy not converted to RF power. As a result of the high efficiency, VE devices are the RF amplifiers of choice for systems with volume, weight or prime power constraints, such as satellites, UAVs, airborne ECM pods and mobile radar and communication terminals.



Progression of Device Power Density, $P_{av}f^2$, for Major VE and Solid State Device Types (Figure 6)

ECM systems require wide bandwidth combined with high efficiency. High gain helix TWTs , which have wide band performance, are the preferred RF amplifier technology for these applications. In the MPM and MMPM, the gain of the vacuum power booster (TWT) is intentionally reduced. This results in a further increase in power-bandwidth product. Future ECM applications, such as towed decoys, airborne self-protection, and support and escort jammers, will continue to use helix TWTs and MPMs.

RF power at millimeter-wave frequencies is exclusively the domain of Vacuum Electronics due to the larger physical size of the interaction structures and the vacuum transport medium. Millimeter wave slow-wave devices (Helix and TWTs and MPMs) are capable of higher power than any solid state device. Even higher powers are achieved by Coupled Cavity TWTs and Extended Interaction Klystrons. Fast-wave devices (Gyro-Klystrons, Gyro-TWTs) can produce very high RF power at high frequencies. The NRL Gyro-Klystron has demonstrated 100 kW peak and 10 kW

average power over a 4% bandwidth at 94 GHz. Future military systems applications for millimeter-wave RF devices include high-data-rate communication terminals, communication satellites and high-resolution radar.

New radar systems are increasingly using active phased array architectures. The use of VE devices in phased arrays has not been fully exploited. Small cross section MPMs can be used for arrays with half wavelength element spacing up to X-band. MPMs can deliver more peak and average power with large bandwidth, high efficiency, low distortion and short pulses than solid state modules. For higher frequency applications, MPMs can be used to drive sub-arrays. MPM technology can provide a higher performance, lower cost alternative to WBG solid state modules. Improvements in phase shifter and circulator technologies will further enhance the performance of arrays using MPMs.

Dr. Parker presented some examples of VE technology advances to upgrade fielded systems and to meet increased system performance requirements.

Significant radar detection improvements in the AN/SPY-1 radar are needed to counter Anti-Ship Cruise Missile (ASCM) and Tactical Ballistic Missile (TBM) threats. A 20 dB improvement in clutter rejection is needed to detect ASCMs in littoral environments and a 16 to 26 dB improvement in TBM detection sensitivity is needed to meet projected Navy Theater Wide requirements. During the projected 40-year service life of the current AN/SPY-1 radar, introduction of a high-gain, low noise Multiple Beam Klystron (MBK) to replace the existing Crossed Field–TWT amplifier chains could enhance radar sensitivity by about 12 dB. S-band MBKs with 40 dB gain are capable of producing 600 kW peak and 60 kW average RF power at 50% efficiency with up to 20% bandwidth and noise levels of –90 dBc/MHz. This is the most cost-effective approach, as it preserves the existing array architecture.

The Army's Secure Mobile Anti-Jam Reliable Tactical Terminal (SMART-T) is a 43.5 to 45.5 GHz satcom uplink. To achieve 100% link availability with a 10Mbps data rate requires a transmitter power of 75 to 80 watts. With the limited transmitter package volume available, a pHEMT transmitter provides only 25 to 30 watts of RF power. This results in loss of communications under adverse weather conditions. An MMPM is being developed to initially provide 40 to 50 watts CW with 25% DC to RF efficiency in a 4 lb., 35 cu. in. package. In later versions, the RF power will be increased to above 75 watts CW. Even higher RF power of 120 watts CW is available using a helix TWT transmitter. However, this approach requires a larger package volume.

The AN/TPQ-47 Firefinder artillery and missile tracking and locating radar replaces the earlier AN/TPQ-37 corporate fed phased array system. System trade studies were performed comparing five architectures:

- Direct modification of the existing TPQ-37
- Bistatic multi-aperture concept
- Single or multi-aperture frequency scanning
- Solid state active array
- Hybrid phase/phase scanning array

The Hybrid ESA best satisfied the Firefinder program goals for performance enhancement, mobility (small size and weight), high reliability and low risk and cost. The hybrid ESA incorporates

active solid state receive modules at each radiating element. The transmitter RF power is provided by 17 S-band Power Amplifier Modules (PAMs). The 17 PAMs each drive 24 subarrays. Each sub array in turn drives 6 antenna elements.

A Vacuum Electronics PAM was selected over a competing solid state (SiC SITs) PAM, due to its higher peak to average power capability, higher efficiency, and lower technical and production risk. The use of modern VE design technologies resulted in higher TWT efficiency (>40%) and greater reliability.

Note: A more detailed description of the Firefinder radar is in the presentation by Mr. Jeff Guild of Raytheon.

The U.S. Air Force Towed Decoy SPO (ASC/SMNA) expects to buy large quantities of High-Power Fiber Optic Towed Decoys (HPFOTD) each year for 10 to 12 years to protect large RCS aircraft left vulnerable by the lower power decoy developed by the Joint USAF/USN IDECM program. The decoy transmitter approach is based on the MPM concept in order to provide the highest power and meet the ALE-50 launcher dimensional constraints. Currently, the required RF power levels can be achieved over the 4.5 to 18 GHz band. Extended frequency coverage from 2 to 18 GHz is being developed on the Ultra-Wideband MPM program that will be demonstrated early in CY 2001. Future improvements in power, linearity and efficiency will be needed to support the HPFOTD applications. The cost goals of $10K to $15K per MPM are challenging and will require ManTech efforts for design to cost and manufacturing process improvements.

Very high-resolution radar is required to conduct space surveillance on increasingly smaller satellites. MIT/LL and U.S. Space Command are in conceptual development of the Haystack Ultra-Wideband Space Imaging Radar to meet this need. The radar calls for a transmitter with 8 GHz instantaneous bandwidth at 96 GHz and peak RF power of at least 5 kW at duty cycles of 20%. The development of an extremely wide-bandwidth W-band TE01 mode Gyro-TWT is proposed, based on the current success of the NRL, industry and university programs in Gyro-amplifier research.

Dr. Parker summarized the NRL Vacuum Electronics S&T Program, which has six areas of technology emphasis. These are:

- Multiple-beam amplifier (MBA) technology for high power, low noise radar applications.
- Linear and wide-band amplifier technology, both VE devices and MPMs for electronic warfare and communications.
- Slow-wave millimeter-wave amplifier technology at Ka-band to W-band
- High-power millimeter-wave gyro-amplifier technology at Ka-band and W-band.
- Modeling and simulation – development of an integrated suite of device design codes.
- Sub-component technology including materials, electron emitters and dielectrics

The Multiple-Beam Klystron (MBK) can produce high peak and average power, high efficiency, and a 50dB improvement in phase noise compared to current Crossed Field Amplifiers. The MBK technology has been demonstrated in Russia. MBKs use several electron beams interacting with cavities or circuits within one vacuum envelope. This lowers the operating voltage, leading to compact, lower weight transmitters. The primary technical challenge is the successful development and demonstration of a multiple beam electron gun and focusing system. The use of advanced 3-D modeling and simulation codes makes this development possible.

Research and development of Helix TWTs and MPM Power Boosters (low gain TWTs) is continuing to improve linearity, bandwidth, power and efficiency. VE is the only technology available to meet the growing need for high-data-rate communications and advanced electronic counter measures. To support communications requirements, specific efforts are planned to increase RF power capability to 0.3 to 3 kW CW power with bandwidths from 500 MHz to 3 GHz in the frequency regime of 30 to 100 GHz. Improved phase linearity and a 10dB reduction in intermodulation products while maintaining high efficiency are also goals. For EW needs, the power-bandwidth capability of MPMs and MMPMs is being increased. Ultra-wide band MPM technology is being advanced to increase fundamental power amplification by reducing harmonic power generation, resulting in operation over the entire 2 GHz to 18 GHz band. In the millimeter-wave band, 18 GHz to 40 GHz, RF circuit technology is being developed to provide higher power with enhanced linearity and efficiency. The development of 3-D computer simulation codes and advanced materials and assembly processes will be required.

Extended Interaction Klystrons (EIKs) and Coupled-Cavity TWTs (CC-TWTs) are important technologies for millimeter-wave radar and missile seekers. Device development is focused on increasing bandwidth, efficiency improvement and weight reduction. Development of CC-TWTs at W-band will continue, including demonstration of 1 kW peak, 100 W average power, 4 GHz bandwidth at 94 GHz for SAR and ISAR radar applications. An EIK amplifier is being developed to provides 1 kW peak power with 2.4 GHz bandwidth for UAV-based SAR applications.

High power millimeter-wave amplifiers are needed for surveillance and instrumentation radars. The gyro-amplifier is the only technology that can meet the performance requirements. This capability has been demonstrated by the successful development of the 100 kW peak, 10 kW average, 94 GHz Gyro-Klystron by the NRL, industry, and University team. Development of a 100 kW, 35 GHz Gyro-TWT with 4 GHz bandwidth is planned for range instrumentation radar, with subsequent development of a 5 kW peak, 8 GHz bandwidth Gyro-TWT at W-band for space-surveillance radar.

NRL has a highly successful program to develop accurate 2-D and 3-D modeling and simulation computer codes for Vacuum Electronic devices. These codes provide effective tools to accurately predict device performance, conduct tradeoff analyses and optimize designs. The use of these codes is accelerating the advancement of VE technology, as well as dramatically reducing development time and risk. Current versions of these codes are being used throughout the U.S. VE industry, and first pass design success has been demonstrated in a number of programs. Continued improvement of this computational capability is essential to the development of next generation VE devices. Details of the NRL code development are given in Dr. Baruch Levush's presentation.

Advanced materials are used in VE devices to increase electron emitter life, enhance heat transfer, control RF instabilities, optimize frequency characteristics and focus electron beams. The limitations of currently available materials continue to be key barriers to performance and cost improvements in VE devices. This is particularly true for devices operating at millimeter-wave frequencies, where smaller device dimensions lead to increased power densities. There are four key areas of materials development:

- Lossy Dielectrics – BeO-SiC ceramic composites are used to suppress instabilities and internal reflections in VE devices. All production of this material has been stopped due to health and environmental concerns associated with it. This leaves only one BeO-SiC source in the U.K. NRL has initiated the development of an Aluminum Nitride-based

replacement material and is improving lossy ceramic diagnostic techniques, software, and is also performing material characterization.

- CVD Diamond Supports – CVD diamond, with the highest thermal conductivity and low dielectric constant, is an ideal material to replace existing BeO and anisotropic pyrolytic boron nitride (APBN) supports in Helix TWT circuits and depressed collectors. The use of this material will significantly increase the average power and bandwidth performance of VE devices. R&D is needed to address fabrication, brazing and assembly processes as well as techniques for applying distributed loss to control stability and reflections.
- Advanced Electron Emitters - Advances in high-current-density cathodes will improve the performance and life of VE devices, particularly at millimeter-wave frequencies. Scandate cathodes may provide current densities of 10 to 50A/cm^2 that will improve device efficiency and reliability. High current density cathodes are also needed for Multi-Beam Amplifiers.
- Rare-earth Permanent Magnets-These materials are used to magnetically confine the electron beam and achieve optimal spatial position for RF interaction and collection. Objectives of this project are the development of magnet stacks with higher temperature stability and improved electron beam optics and compact magnet circuits for smaller, lighter weight VE devices, such as those required in the MPM.

Dr. Parker identified needs for Advanced Development and ManTech programs.

The highly successful development of the MPM technology has been demonstrated at microwave and millimeter-wave frequencies. MPMs and MMPMs can meet the needs of a number of military systems including ECM, towed decoys, high-data-rate communications and UAV radar. Advanced development and ManTech programs are needed to incorporate design enhancements, improve the producability, lower the cost and demonstrate the reliability of these devices for specific applications.

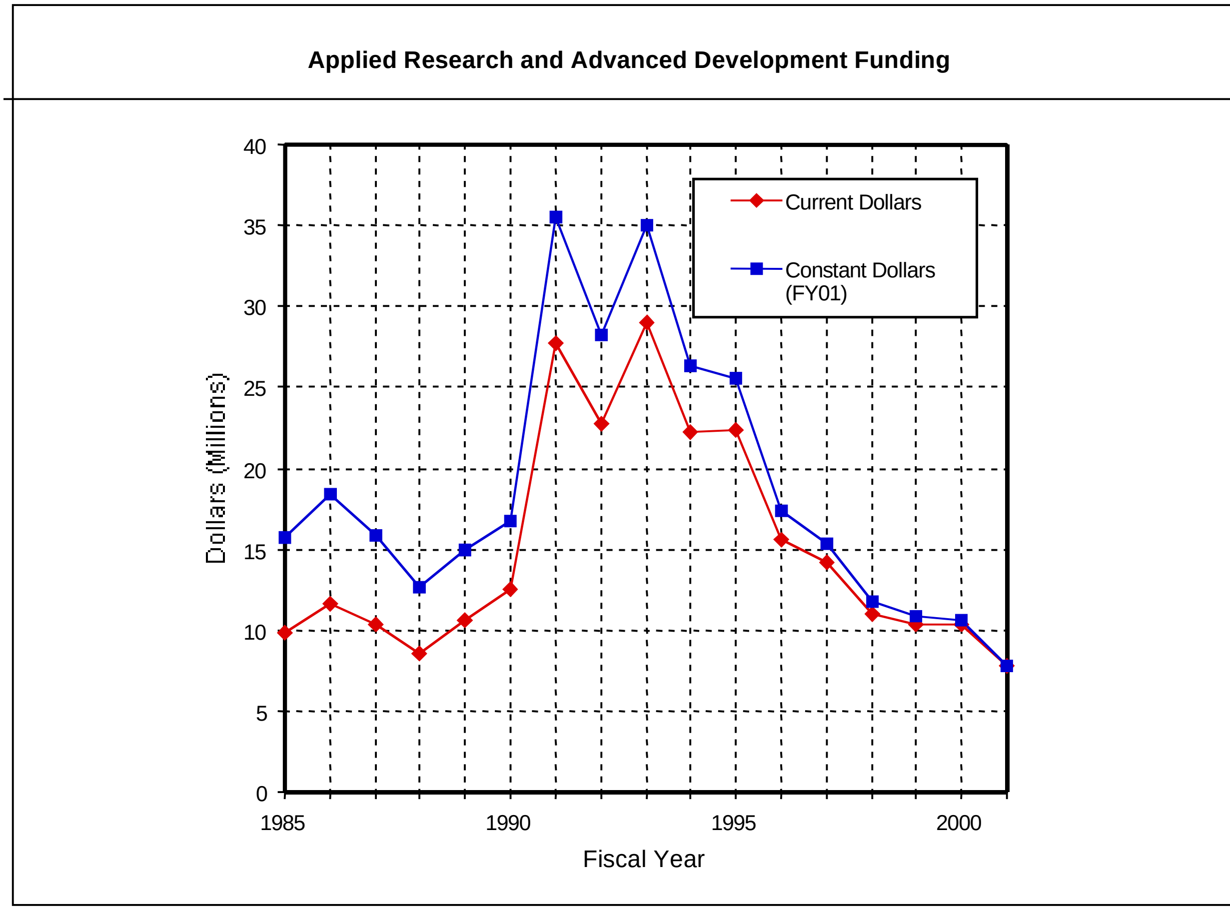
Advanced development efforts are also needed to mature the Gyro-Amplifier technology and develop specific amplifiers to meet the high power millimeter-wave needs for range instrumentation and surveillance radars. Devices need to be developed at Ka- and W-bands with wide bandwidth (4 to 8 GHz) and high power (5 to 100 kW).

Following successful demonstration of a prototype S-band MBK to replace the CC-TWT and CFA amplifier chain used in the SPY-1 AEGIS radar, an advanced development program is recommended to refine the design to a production ready status.

Development is needed to apply advanced materials technologies to specific device designs. These efforts will involve the redesign of sub-components, development of brazing and assembly processes, specific device fabrication and performance testing and qualification.

Dr. Parker reviewed the history of Vacuum Electronics S&T funding and expressed concern over the significant decline in funding.

The current FY01 level of S&T funding for Vacuum Electronics is only $7.7M, down from the $30M to $35M levels in the early 1990s. This is shown in Figure 7.



History of DoD Funding of Vacuum Electronics S&T
(Figure 7)

The current funding is well below the critical threshold to sustain vacuum electronics technology advances. At this level, there is negligible funding for industrial efforts, and limited funding to continue promising R&D technology development at NRL. The VE S&T funding comes almost entirely from the Navy, the lead VE technology center under Project Reliance.

Dr. Parker strongly recommended that the Vacuum Electronics S&T funding be increased to at least $12M to $13M per year for five years. This will continue the significant advances in VE technology, device performance and computer design tools needed to meet the identified Tri-Service needs. This is essentially the same as the FY88 funding (FY01 constant dollars).

Since FY88, basic research (6.1) funding has declined from $7.4M (FY01 constant dollars) to $2.3M, a decline that has greatly restricted the numbers of university students and faculty and innovative research in the field. The major funding source for university efforts is the VE MURI, which has a three-year funding cycle. This short cycle does not adequately support the educational goals or provide continuity of scientific effort. It was recommended that the MURI funding be increased to $4M to $5M per year and the cycle be increased to five years. This will sustain the current robust University research programs and provide a critical source of talent needed to maintain the U.S. technology base.

The NRL VE applied research (6.2) program has resulted in impressive advances in technology and performance. These include the MPM, the W-band Gyro-Klystron, and the modeling and simulation code suite. Applied Research funding of $12M per year is needed to maintain these efforts and achieve the full capability of the technology.

Advanced development (6.3) funding for VE is less than $0.2M in FY01. A funding level of $7.5M to $10M per year is recommended to support efforts by Industry to transition advanced technology VE devices to a production ready state for use in military systems. The availability of several promising VE technologies has suffered from the lack of Advanced Development funds. The specific VE devices identified for these programs include MPMs and MMPMs, millimeter-wave slow wave amplifiers, Gyro-amplifiers and Multiple-Beam Klystrons.

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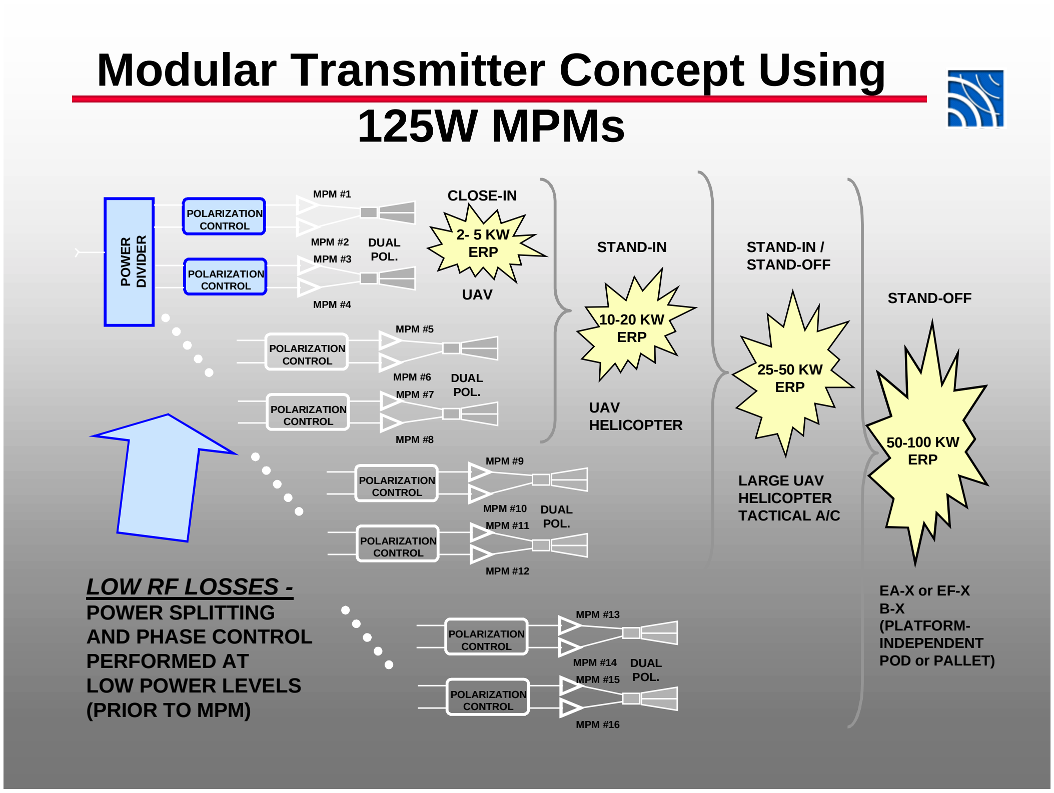
APPENDIX D: PRESENTATION SUMMARIES -- INDUSTRY

Mr. Ron Langietti – Northrop Grumman – EW System Applications

Future transmitter systems will be required to handle communications, radar, and electronic warfare (EW) functions, simultaneously. Today's conventional system architectures employ separate RF transmitter assets for unique communications, radar, and EW functions. Significant trends in radar and electronic counter measure systems are pushing towards the capability of a system to perform multi-functional tasks and support future integrated RF sensors. This implies electronically steered wide band arrays and modular architectures for the transmitter. Modular systems using MPMs can meet a multitude of system power requirements ranging from hundreds watts to hundreds of kilowatts, using relatively low power (i.e., 1 watt to 200 watts) RF amplifiers. A Northrop Grumman modular EW transmitter concept is shown in Figure 8.

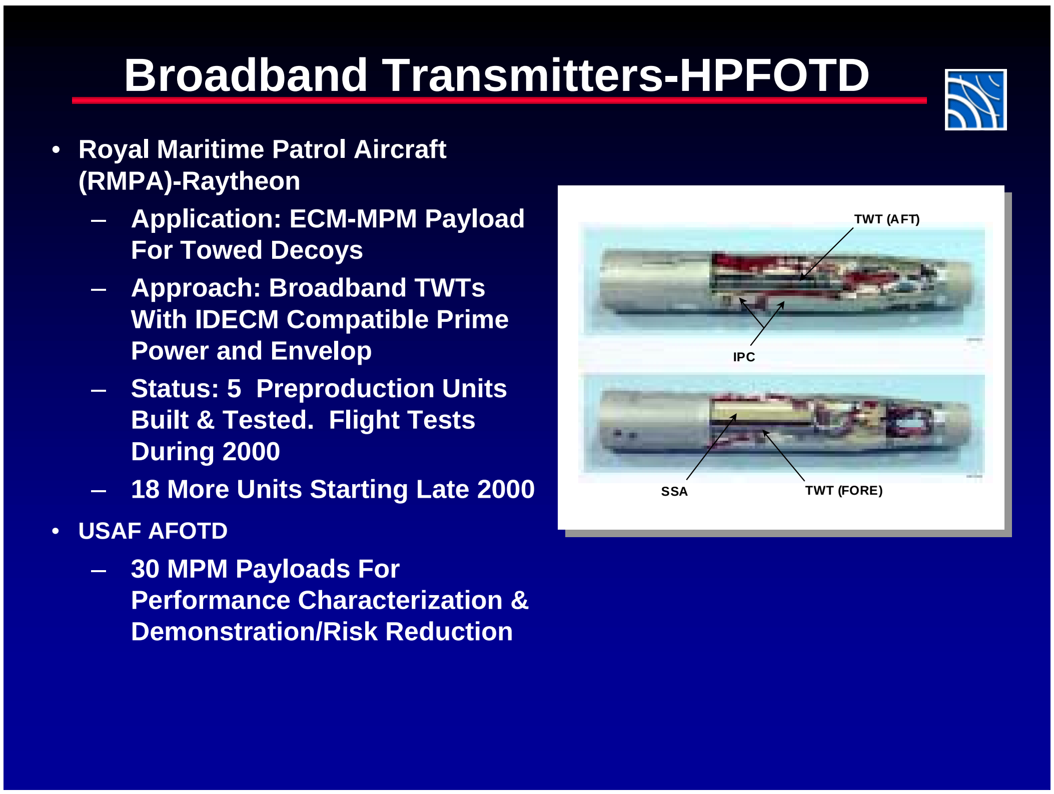


Modular Transmitter Concepts Using Microwave Power Module
(Figure 8)

Miniaturization of the transmitter modules enables the system designer to envision new transmitter concepts previously not realizable. Physically small, high power transmitters can be located directly behind the radiating aperture, eliminating RF losses due to cabling. This reduces the RF output requirements of the transmitter, which in turn, reduces the prime power and cooling required for the system. MPMs, which utilize helix TWTs, are ideal for EW transmitter applications for the following reasons: the ultra-wide bandwidth covers the entire missile frequency band; the small size permits multiple MPM transmitters to be combined or located close to the antenna; the high power conversion efficiency (DC to RF) results in less prime power and cooling. MPMs can operate at higher temperatures than solid state amplifiers and the higher RF power yields the smaller

aperture size and broader beam width that is desired for airborne support jammers. At Northrop Grumman, MPMs are being used in a multitude of transmitter applications ranging from single MPMs driving a single aperture to multiple MPMs being either power combined through corporate or spacial power combining techniques or phase arraying.

There is increasing demand for Towed Decoy ECM capability to protect personnel and aircraft. In contrast to on-board ECM systems, towed decoys offer the advantages of protection against monopulse angle tracking radars, decreased interference with other on-board systems, protection against homing in on the signal jam, and low aircraft installation cost. Specially packaged MPMs provide the high RF power, efficiency and bandwidth in the required form factor for Towed Decoy applications. A Towed Decoy MPM is shown in Figure 9.



Northrop Grumman High Power Fiber Optic Towed Decoy With TWTs
(Figure 9)

From an EW perspective, the technology development trend is towards miniaturized very wide-band high power amplifiers that have superior linearity properties enabling multi-function operation. Linearization techniques have been widely used to support the needs of the communications industry, however linearization will begin to play a significantly more important role for both ECM and Radar systems. The wide bandwidth requirement will allow the same transmitter asset to be used to support multiple system functions that fall within the operating bandwidth of the transmitter. Northrop Grumman’s 2 to 18 GHz MPM development efforts are pushing the state-of-the-art in terms of bandwidth/power output product. Additional development will need to occur to further push the power/bandwidth product to higher levels of performance and significantly higher operating frequencies. Millimeter Wave (MMW) transmitters will play an ever increasing role in EW system applications. Already, the trend is to push the usable spectrum even higher, which will result in increased demands on EW systems.

Northrop Grumman has been focusing on the development of both narrow and wide bandwidth helix traveling wave tubes (TWTs) for use in miniature microwave and millimeter-wave power modules (MPMs and MMPMs). MPM technology has found wide acceptance within the military community (both U.S. and foreign) for use in remote transmitter applications. Future EW systems are being developed that will use MPM and MMPM technology. Military communications and radar applications are also investigating the use of MPM and MMPM technology for enhanced system performance. Several of the system requirements that are driving the RF transmitter development trends in microwave and MMW vacuum electronics device technology are shown in Table 1 below.

Table 1: MPM and MMPM System Requirements and Applications

Applications	**Key System Requirements**	**Technology Implementation / Trends**	**Northrop Grumman System Applications**
Electronic Counter Measures (ECM)	Wide bandwidth, high output power, small size / weight	Stand Alone MPMs driving single aperture, power combined MPMs driving a single aperture, multiple MPMs in a phased array application, multiple MPMs driving a single dual polarized aperture, and towed decoys	Remote ECM transmitters for F-16, F-15, … future high power phased arrays. Foreign ECM / radar applications. High power MPM based transmitters power combining multiple MPMs. MPM technology packaged for towed decoys
Military Communications	High output power, narrow bandwidth, high efficiency (i.e., ~ 50%), small size and weight	MPMs in a circular phased array architecture. Single MPMs driving single aperture	Cooperative Engagement Capability (CEC), SATCOM
Radar	High output power, high efficiency (i.e., ~ 50%), small size and weight	Multiple MPMs in a direct feed phased array architecture. Single MPMs driving power splitters / multiple apertures	Low cost radar applications
Commercial Communications	Narrow bandwidth, high efficiency (i.e., ~ 50%), small size and weight	Multiple MMW power modules driving wide FOV apertures	MMW power modules for use in LMDS base stations
MMW ECM	Wide bandwidth, high output power, small size / weight	On-board and off-board (towed decoy) transmitters	Future ECM requirements
Other	Both wide and narrow bandwidths, high to medium output power, small size and weight	Single MPMs driving single apertures	ECM

The Microwave Power Module (MPM) continues to enable sophisticated high power transmitter system architectures over the 2 to 40 GHz frequency band. From an EW perspective, the

MPM provides the system designer with a tool that has yet to be matched by any other technology. It offers very high power at high efficiency in a compact package that can be located in tight volumes on the host platform. On-going Northrop Grumman development efforts pertaining to the development of the 2-18 GHz MPM as well as the 18 to 40 GHz MMPM will greatly enhance future EW systems. New system architectures that best utilize the performance of VE technology need to be explored. For phased array applications, when considering higher power per array elements, vacuum electronics/MPMs become strong candidates. The MPMs provide very broad bandwidth, often well over an octave, and power levels of hundreds of Watts. For multi-function phased array transmitters, VE technology offers significant advantages in performance (high power per element resulting in wide field of view (FOV) radiation patterns), reliability (gradual degradation), operational availability, and supportability (same VE used in multiple applications).

Additional investment could determine new EW system requirements and RF power amplifier needs. Detailed modeling and trade studies need to be performed to understand which technology (solid state or vacuum electronics) will best meet the platform requirements, not only performance but also cost. Technology advances in system concepts, hardware (transmitter as well as support components) performance, detailed component and system modeling, and reliability are needed to be performed. Investment in components (MPMs, high power circulators, phase shifters, antennas, etc.) and transmitter demonstration and evaluation is crucial to successfully meeting future military system needs.

Additional advances in helix TWT performance, reliability and manufacturability are required. Development of VE technology pertaining to field emitter arrays (FEAs), millimeter-wave (MMW) power from 18 to 300 GHz, and very high power needs to be pursued. Producibility investment is required to make sure these technologies are available when needed. Failure to make this investment will almost certainly result in loss military superiority and more importantly loss of lives.

Mr. Jeff Guild, Raytheon

Mr. Guild presented the system tradeoffs that were conducted in the design of the AN/TPQ-47 next generation Firefinder Radar. This mobile artillery and rocket locating radar is a significant upgrade of the earlier AN/TPQ-37 system.

The capability improvements for the TPQ-47 included:

- Increased Accuracy
- Increased Range
- New Targets
- Increased Target Classification
- Increased Target Throughput
- Enhanced User Interface
- Improved Maintainability/Supportability
- Smaller Size
- Anti-Jam Features

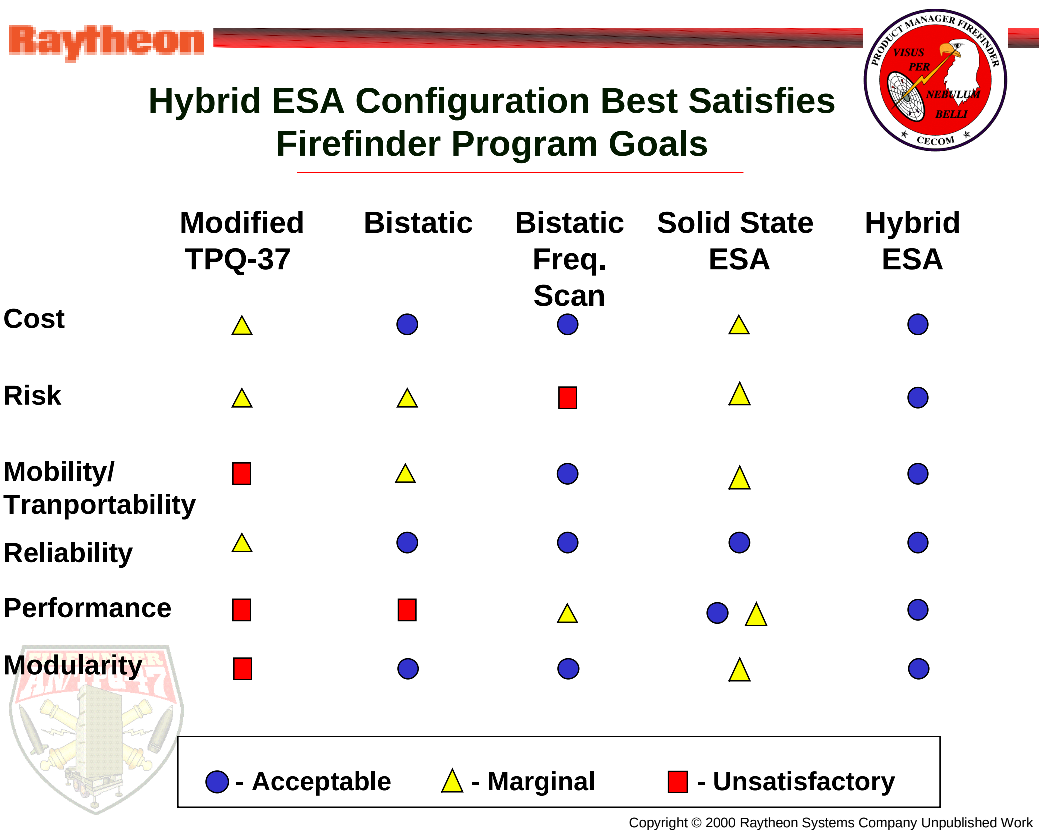
Meeting these challenging requirements required an increase in Signal /Noise of more than 14dB in a smaller, air-cooled package, using the existing 60kw generator. The limited prime power drove the need for maximum transmitter efficiency. Other system architecture features that were desired were:

- Modular Design -Allows Technology Upgrades
- Scalable Design – Supports Mission Adaptation
- Flexible Design – Allows Insertion of New Modes of Operation

Raytheon considered five approaches to meet the TPQ-47 requirements:

- Direct Modification of the Existing TPQ-37
- Bistatic Multi-Aperture Concept
- Single or Multi-Aperture Frequency Scanning Array
- Solid State Active Electronic Scanned Array
- Hybrid Phase/Phase Scanning Array

The results of the trade study are shown in the table below (Figure 10).

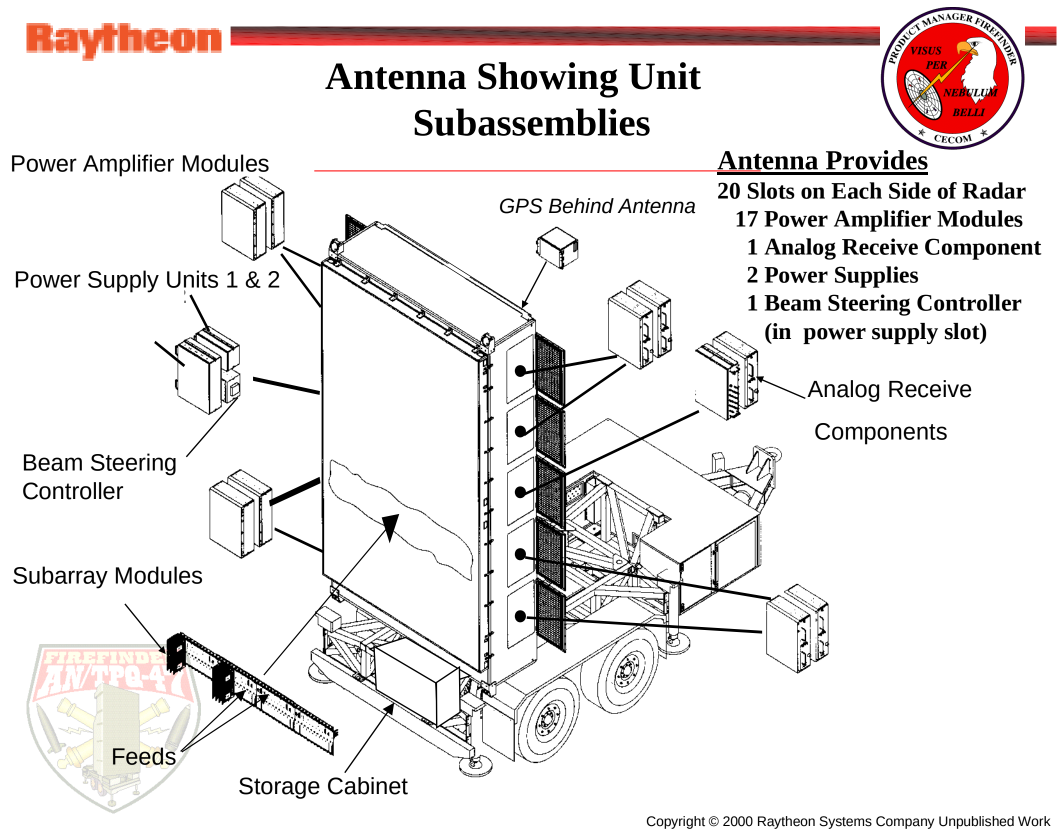


	Modified TPQ-37	Bistatic	Bistatic Freq. Scan	Solid State ESA	Hybrid ESA
Cost	△	●	●	△	●
Risk	△	△	■	△	●
Mobility/ Tranportability	■	△	●	△	●
Reliability	△	●	●	●	●
Performance	■	■	△	● △	●
Modularity	■	●	●	△	●

(Figure 10)
System Architecture Trade Study For the TPQ-47 Firefinder Radar

The Hybrid ESA Configuration satisfied all of the Firefinder Program Goals and had advantages over the Solid State ESA in cost, risk, mobility (size), and modularity. This approach provides nearly all of the performance advantages of an active ESA and is compatible with both VE and solid state RF device technologies.

The TPQ-47 antenna array is shown in the following figure.



Firefinder TPQ-47 Antenna Array with VE-Based Power Amplifier Modules
(Figure 11)

The array incorporates approximately 2500 radiating elements that are controlled by subarray modules that radiate and receive RF and steer the beam. The array transmit power is provided by 17 Power Amplifier Modules (PAMs). The receiver array functions are provided by MMIC receive modules.

The initial program proposed to use solid state PAMs that used power combined wide bandgap SiC devices. However, the SiC device technology was not sufficiently mature and could not meet the power, pulse width and efficiency requirements.

A TWT based PAM, that meets all technical requirements, was selected for the system EMD. This PAM uses a pulsed TWT and a high efficiency resonant converter power supply.

The PAM requirements include:

Average RF Power Output	500 W
Efficiency	>25%
Duty Factor	<10%
Cooling	Forced Air
Weight	65 lbs. (goal is <37 lbs.)
Size	26” X 19” X 8”

Raytheon believes that this Hybrid ESA architecture that uses both VE and solid state RF technologies will be effective for other mobile radar applications where low weight, high efficiency and affordability are primary requirements.

Dr. Carter Armstrong - Litton Electron Devices

Dr. Carter Armstrong presented Litton EDD’s vacuum electronics device development achievements and technology thrusts. Litton EDD is one of the two largest producers of VE devices in the U.S. Litton produces a wide range of VE devices, including high power klystrons and fast wave gyro-devices, crossed field amplifiers, coupled cavity and helix TWTs, and microwave power modules (MPMs) for military and commercial applications.

Dr. Armstrong described Litton’s VE technology thrusts in the following areas:

- Microwave and Millimeter-Wave Power Modules (MPMs)
- Folded Waveguide TWTs
- Harmonic Gyro-klystrons
- Multi-Beam Klystrons
- Intelligent Automation

Litton has developed a line of MPMs that cover the frequency range of 2.0 to 45.5 GHz.

For EW applications, the following MPMs have been successfully developed:

2 to 8 GHz	100 W RF output (Pulsed or CW)	70 cu.in. package
6 to 18 GHz	100 W RF output (Pulsed or CW)	50 cu.in. package
18 to 40 GHz	10 to 20 W RF output	53 cu.in. package

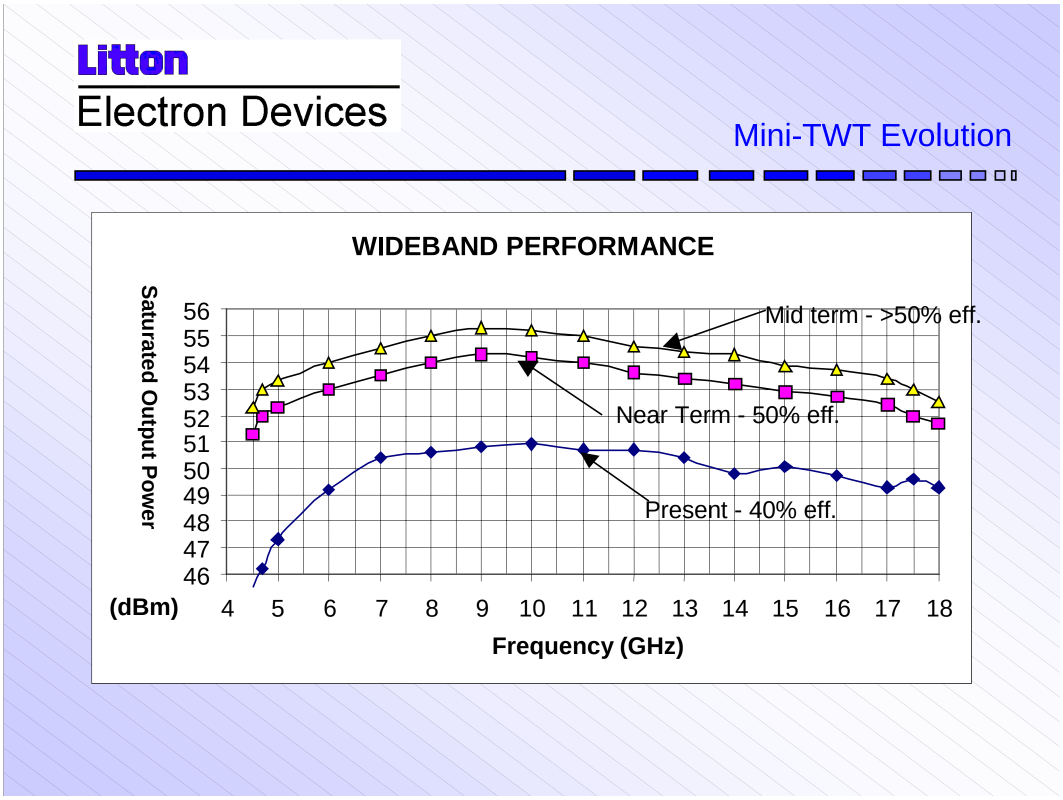
(Figure 12)

The performance of the 18 to 40 GHz MPM is shown in Figure 12.

Narrow bandwidth MPMs are also being developed at C, X, Ku, Ka, and Q-band. They will be used in mobile communication terminals, missile seekers and radar systems where small size and weight and high efficiency are required.

Litton plans to increase the performance of the MPM products through advances in the mini-TWT, the solid state RF driver amplifier and the electronic power conditioner (EPC). These improvements include:

- Increased RF output power to 200 W over the frequency range of 2 to 18 GHz
- Increased RF output power to 80 W over the frequency range of 18 to 40 GHz
- Higher frequency operation at 60 GHz and 90 GHz
- Wider instantaneous bandwidth to cover the entire 2 to 18 GHz
- Higher overall efficiency to >50%
- Improved linearity
- Higher power density EPCs
- Longer Life



Wideband mini-TWT Performance Evolution
(Figure 13)

The evolution of wide-band mini-TWT performance is shown above in Figure 13. Current RF output power is greater than 49 dBm from 6 to 18 GHz, with 40% efficiency. Within the next five years, the output power is projected to increase to above 51 dBm over the frequency band from 4.5 GHz to 18 GHz, with 50% efficiency. These performance improvements will be achieved through the development of the TWT components:

- Higher circuit efficiency through computer modeling and optimization
- Reduced circuit RF losses using advanced plating and surface finishing techniques
- Higher power low loss microwave ceramics
- Support rods (CVD Diamond, APBN, others)
- RF Windows
- Low distortion and high stability interaction circuits
- Multi-stage depressed collectors
- More stages
- Aluminum Nitride ceramic
- Low secondary emission materials
- Improved electron beam optics
- Higher perveance, lower voltage designs
- Ultra-laminar, high convergence designs
- High strength magnetics

In the future, Litton sees significant life improvements resulting from the development of low temperature or cold cathodes, which would eliminate cathode wearout and provide instant turn-on

capability. Emission controlled TWTs will provide variable output power, higher efficiency, improved linearity and extended life.

Technology advances needed in the solid state RF driver amplifiers to improve the performance of MPMs:

- Higher output power SSAs, especially in millimeter-wave frequencies
- Integral adjustable gain equalizers
- Harmonic injection circuits to extend performance down to 2 GHz
- Linearization circuits incorporated into the SSA

Below are improvements in EPC component technologies that will increase MPM efficiency and reduce size:

- Higher speed, more efficient high voltage diodes
- High voltage capacitors
- Planar transformers
- High thermal conductivity potting materials for high-voltage connections
- Advanced regulation techniques

Litton sees future DoD need for compact high performance millimeter-wave amplifiers for secure, high-data-rate communications, EW and missile seekers and high-resolution radar applications. The broad range of RF output powers required for these applications, from 40 W to 20 kW at frequencies from 45 GHz to 95 GHz, can be provided using helix TWTs and MPMs (low power), folded waveguide TWTs (intermediate power) and Harmonic Gyro-klystrons (high power).

Litton is planning the development of a family of millimeter-wave MPMs based on their 40W CW, 45 GHz amplifier for the Army SMART-T mobile satellite ground terminal. The demand for higher data rates will require increasing the RF power level to 80 W and then 150 W. This performance can be achieved using helix TWT technology up to 60 GHz. MPM size and weight projections are 50 to 100 cu.in. and 4 to 7 lbs.

For even higher RF power at millimeter wavelengths, Litton is pursuing the Folded Waveguide TWT. Folded waveguide TWTs are capable of RF powers of 1000 W at 35 GHz and 100s of Watts at frequencies up to 100 GHz. Litton has successfully developed a PPM focused, folded waveguide TWT with 1000 W output at around 30 GHz. This device has greater than 10% bandwidth and operates below 20 kV. High efficiency is achieved using a multi-stage depressed collector.

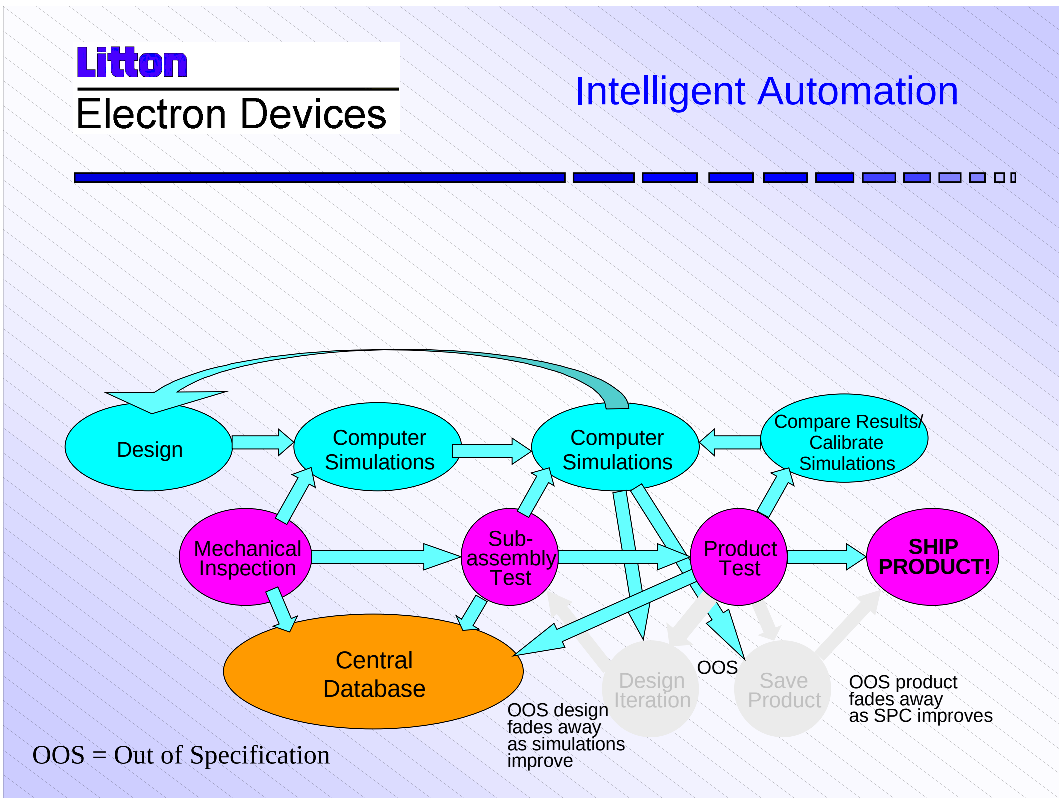
The harmonic gyro-klystron can provide 20 kW peak, 2 kW average RF power at frequencies as high as 95 GHz. This device operates at less than 50 kV and does not require a superconducting solenoid. This is an advanced version of the W-band gyro-klystron that has been developed for the NRL WARLOC radar demonstration.

The MBK has the potential to replace CFAs that are used in heritage S-band Radars and achieve a 50dB reduction in noise. The use of multiple electron beams provides greater bandwidth, higher efficiency and lower operating voltage. The MBK has a phase noise of -90dBc/MHz, similar to a conventional klystron.

The development of the MBK presents several technical challenges. A convergent multi-beam electron gun and beam focusing system must be developed with acceptable cathode loading for long life operation. This will require the extensive use of gun and beam optics 3D computer design codes. The wide band RF circuit will require large signal interaction and cavity cold test modeling as well as stability analysis codes. The multi-stage depressed collector will require 3D optics codes to handle the multiple beam trajectories.

Litton described their "Intelligent Automation" initiative to address issues of VE producibility and reliability. The key elements of this program are:

- Optimized device design and component selection using advanced computer modeling and simulation and performance feedback.
- Intelligent automation to reduce process variability and achieve high yields.



Litton Intelligent Automation Concept
(Figure 14)

Litton recommendations for S&T thrusts that are essential for the continued advancement of VE technology are:

- Modeling & Simulation
  - Complete the development of 3D codes for optics, RF circuits, multi-stage depressed collectors
  - Code validation is essential

- Cathode/Electron Gun Development
  - Ultra-laminar, higher area convergence guns
  - Low temperature cathodes
  - Emission-gated cathodes and TWTs

- High Power RF Circuit Development
  - AlN and CVD diamond materials and processes
  - Advanced, non-toxic ceramics
  - High strength/ high temperature permanent magnets

Dr. James Dayton Jr.-Boeing Electron Dynamic Devices

Boeing Electron Dynamic Devices (EDD) core business is the development and production of TWTs and TWTAs. The majority of EDD's sales are for commercial communication satellite applications.

Thirty percent of EDD's sales are for DoD applications. These are primarily heritage designs that are 20 to 30 years old. In the past several years, DoD S&T investment at EDD has been negligible.

EDD is the only U.S. manufacturer of space TWTs. EDD TWTs are used in approximately 70% of all commercial satellites. These TWTs have accumulated more than 220 million hours of operation in space. For satellites launched since 1990, the observed failure rate is 56 failures per billion hours (178 million hours MTTF). Space TWTAs have a demonstrated lower failure rate than comparable space solid state amplifiers.

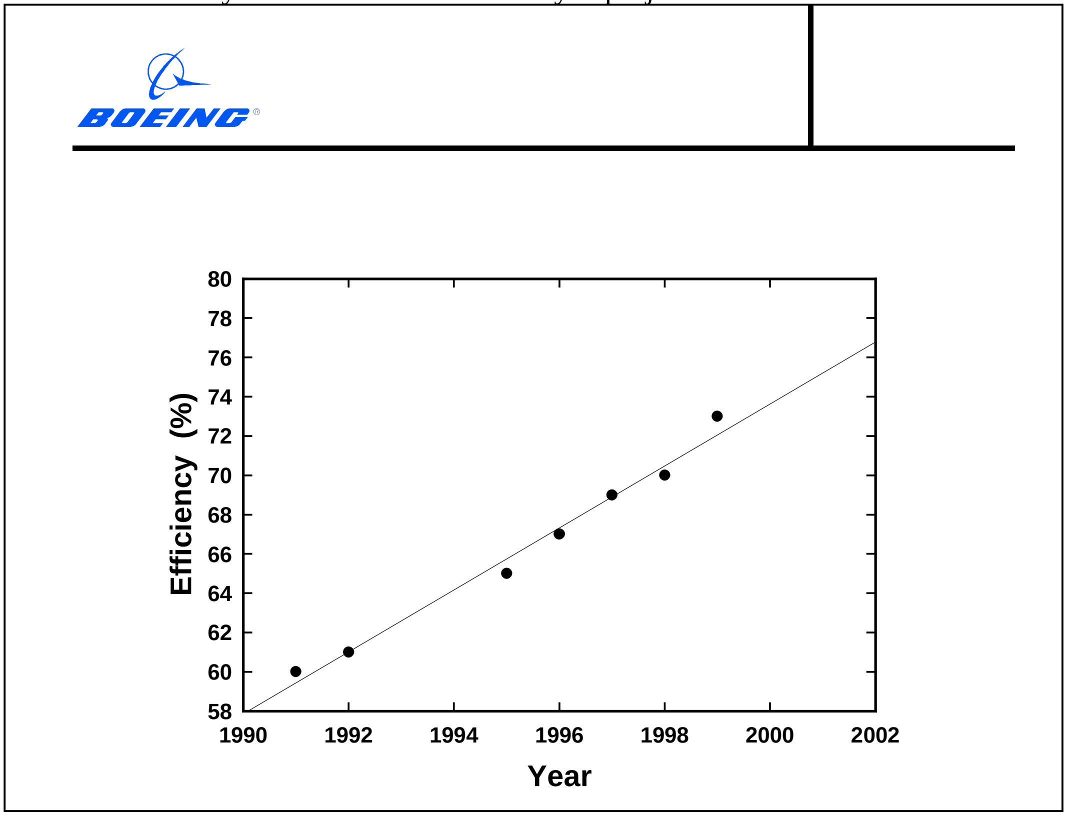
Unlike DoD applications, commercial communications markets demand and facilitate constant performance advances. Current thrusts are improvements in:

- High power at millimeter-wave frequencies
- Efficiency
- Reliability
- Linearity

The technologies developed for these commercial products can be applied to meet unique military system needs.

Dr. Dayton described, on the next page, major technology and performance advances that have been achieved at EDD.

The efficiency of TWTs continues to increase, from 60% in 1991 to 73% in 1999. EDD expects to achieve 75% by 2002 and >80% efficiency is projected in the future.



Boeing Ku-band TWT Efficiency Improvements
(Figure 15)

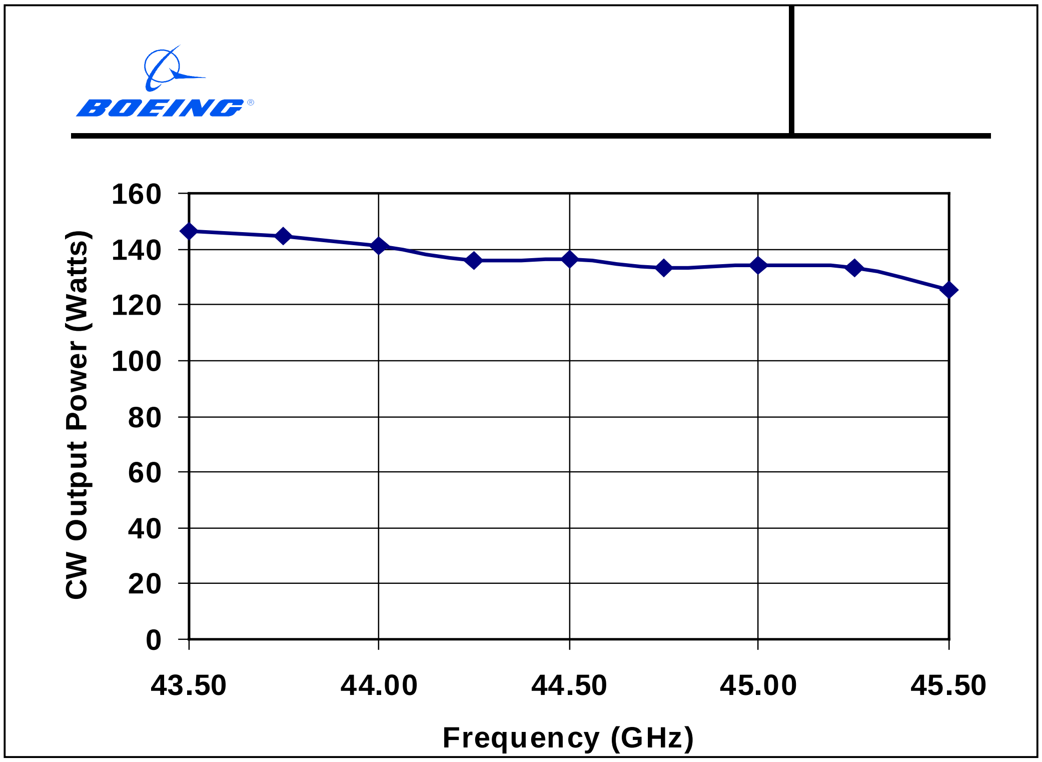
Advanced computer modeling and simulation codes are achieving first pass design success. These codes provide highly accurate (within 1% or 2%) performance and stability predictions from physical dimensions and material characteristics. EDD has developed a set of integrated simulation codes to design all the major TWT components:

- Electron gun
- PPM beam focusing stack
- Helix cold circuit characteristics
- Small and large signal beam-circuit RF interaction and spent beam characteristics
- Multistage depressed collectors
- Thermal and dynamic analysis models
- RF couplers

These accurate models allow for device optimization without cut and try experimental iterations, resulting in higher performance and reduced cost and development time. These codes are equally applicable to the design of TWTs for commercial and DoD applications.

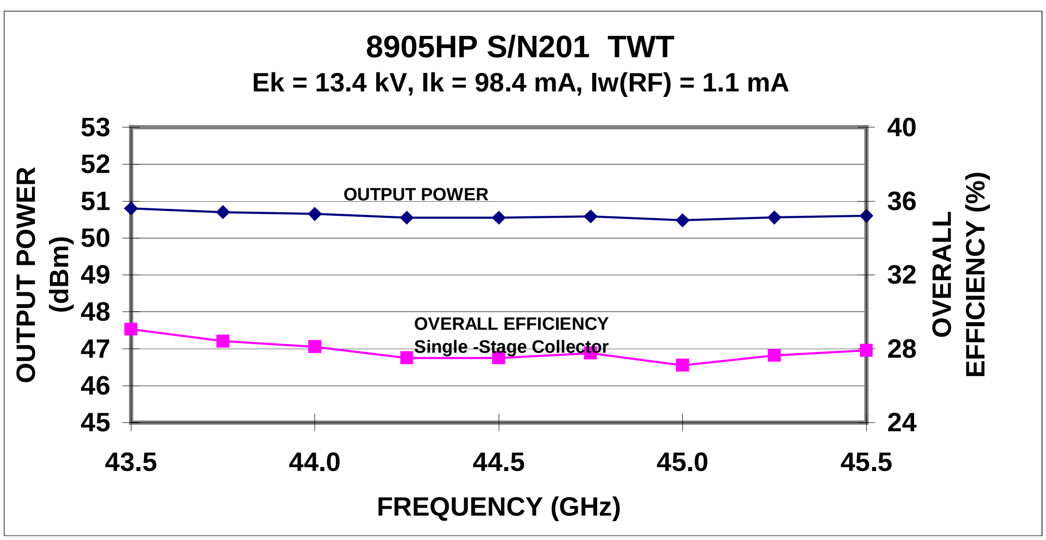
Millimeter-wave Helix TWT technology is achieving new records in performance. EDD has demonstrated RF output powers of up to 150 watts CW at 45 GHz (a new power density [$P_{av}f^2$] record) with absolute stability and small signal gain variations of less than 0.5dB. This TWT also

provides 50 to 100 watts over the entire 40 to 50 GHz band. These designs are applicable to Helix TWTs operating at 30 GHz and higher.



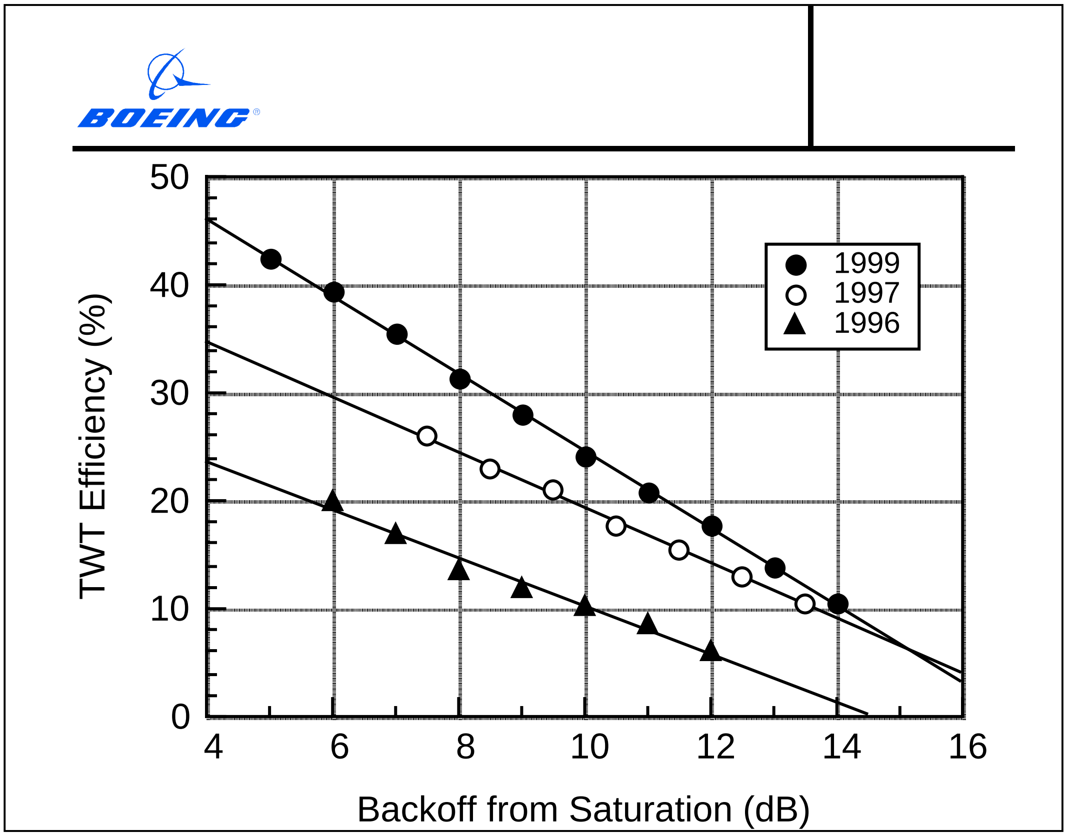
Performance of Boeing Millimeter-wave Helix TWT (8905HP)
(Figure 16)

Multichannel Amplifiers Using High Linearity TWTs Are Much More Efficient Than Comparable



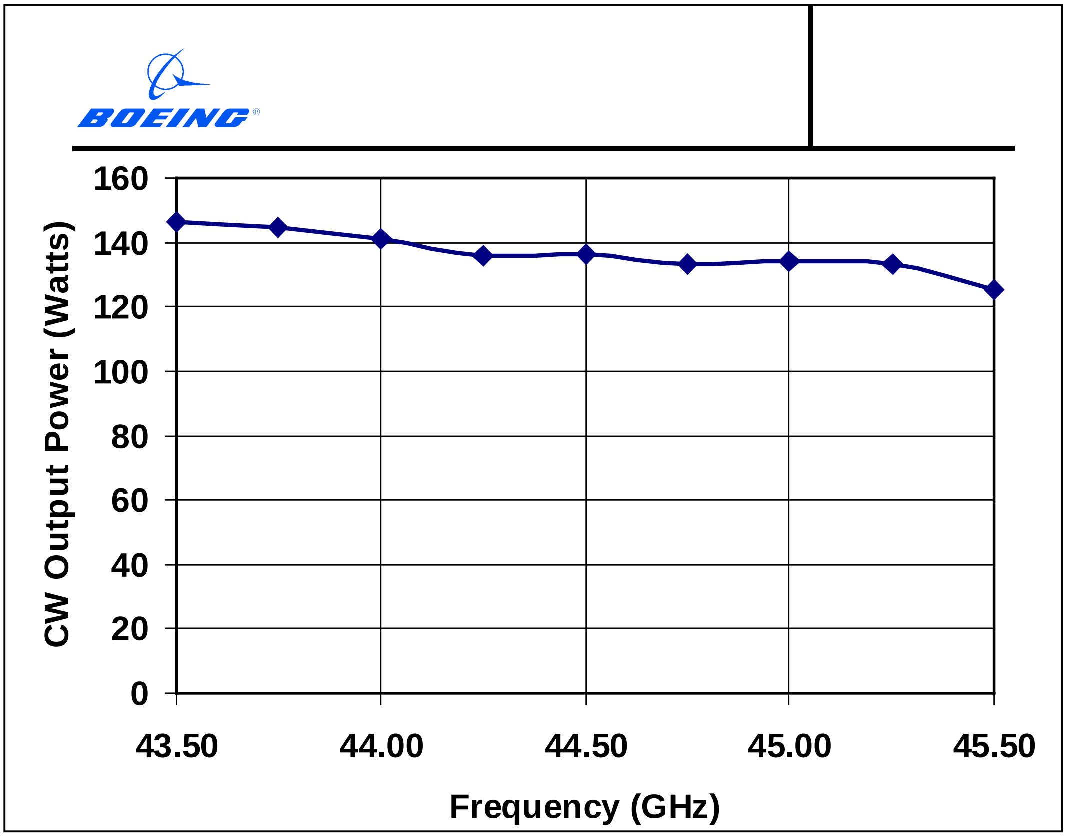
Solid State Amplifiers
(Figure 17)

EDD is developing high efficiency, ultra-linear TWTs for commercial personal communications systems (PCS) telecommunication systems at 1.8 to 2.35 GHz. For these applications, the helix RF circuit design is optimized for low carrier to third order intermodulation products (C/3IM) of 20 to 40 dBc. This is a 5 dB improvement over a standard helix design. The TWT is operated approximately –6 dB below saturation. High efficiency of 40% is achieved using a multi-stage depressed collector to recover the spent beam energy. Using an external linearizer, intermodulation levels of C/3IM of 50 to 80 dBc are achieved. The impact of modern design codes is illustrated (Figure 1 and Figure E)) by the ability to rapidly respond to demand by the system developer for increased efficiency with linearity.



Increased TWT Basic and Collector Efficiencies Have Improved Overall Efficiency With Linear Operation
(Figure 18)

Using these technologies, high linearity, multi-channel TWT amplifiers achieve higher efficiency than comparable solid state amplifiers.



Saturated Output Power
(Figure 19)

EDD identified the current technical barriers to achieving higher RF power and efficiency as follows:

1) Limitations in computer modeling and simulation codes, including 3D collector modeling, spent beam characterization, and thermal-mechanical design models.
2) Inadequate knowledge (temperature and frequency dependence) and control of material properties.
3) Fabrication techniques to achieve the exacting tolerances required at millimeter-wave frequencies

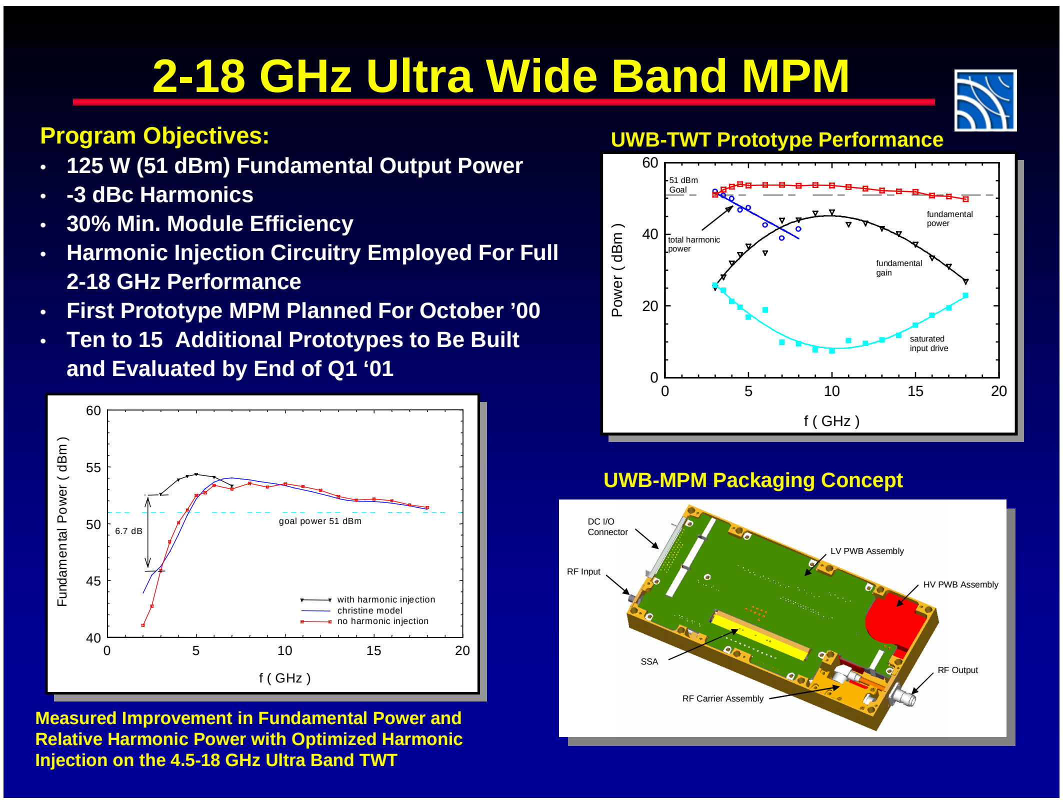
EDD made the following recommendations for upgrading existing VE based systems and developing supporting technologies:

- Many VE devices used in fielded DoD systems that were designed more than 20 years ago could be made much more reliable and efficient using modern design codes.
- Improved power supply component (high frequency solid state devices, planar transformers, etc.) will reduce the size and improve the efficiency and reliability of VE transmitters and MPMs.
- Linearizer technology, developed for commercial telecommunications markets, should be extended to DoD applications frequencies.

Mr. Ron Langietti – Northrop Grumman

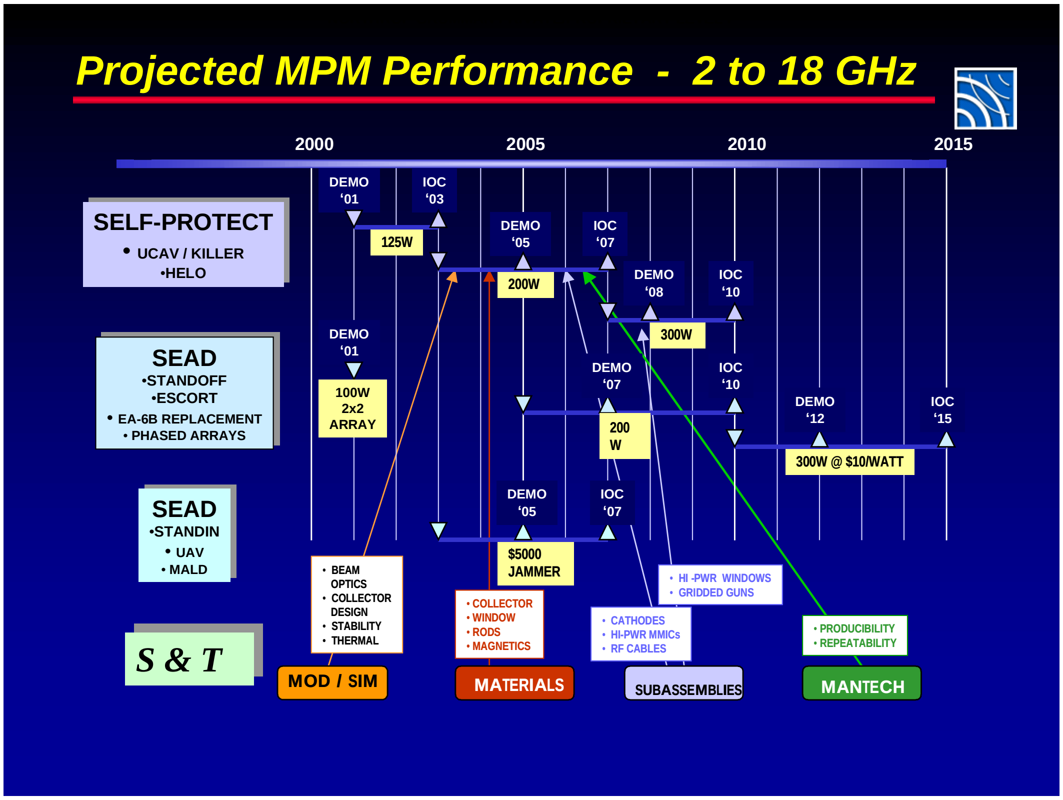
Northrop Grumman's primary VE technology thrust is the development of TWTs and MPMs for EW applications. The EW technology development trend is towards miniaturized, very wide bandwidth and high power transmitters. This has led to the development of very high efficiency, high power TWTs for use in MPM applications. Northrop Grumman's development of a 125 watt, 2 to 18 GHz MPM with >30% efficiency is extending the state-of-the-art in power/bandwidth product.

A Northrop Grumman TWT has achieved 125 watts RF output power over the 3 to 18 GHz band, shown in Figure 9. This performance is being extended down to 2 GHz using harmonic injection technology in the solid state driver. This is a continuation of the increases in bandwidth that have been achieved in the last 5 years.



Performance of Northrop Grumman's Ultra-Wide Band MPM
(Figure 20)

The development roadmap for the 2 to 18 GHz TWT for this MPM is shown in Figure 20. These efforts will require continued improvements in 3D computer modeling and simulation codes to improve beam focusing, RF stability and efficiency. Advanced dielectrics and circuit fabrication processes are needed to increase RF power capability. Development of low temperature cathodes will increase life and efficiency. Solid state RF drivers with higher output power, more bandwidth and harmonic drive capability are also needed.



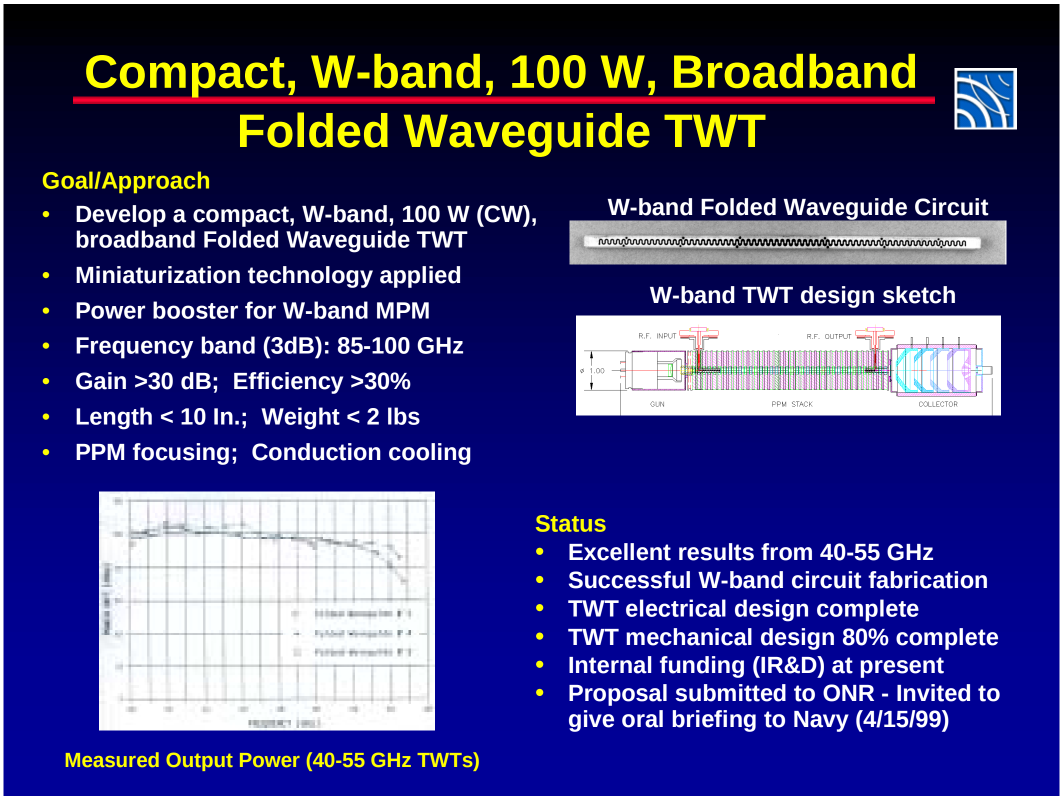
Northrop Grumman Development Roadmap for a 2- to 18 GHz TWT for the MPM
(Figure 21)

Northrop Grumman is also developing a TWT for millimeter-wave MMPM applications, to meet new EW systems demands. A 20 to 40 GHz TWT is in development that provides 50 to 80 watts RF power with a maximum of 300 watts prime power. Future plans call for increasing the RF power to >100 watts near term and >200 watts far term. This will be more difficult than the 2 to 18 GHz TWT development due to the 3 times smaller dimensions and resulting higher power densities at millimeter-wave frequencies.

MPM technology has found wide acceptance within the military community (both DoD and foreign) for use in miniaturized transmitter applications. Future EW systems are already being developed that will use MPM and MMPM technology, including power combined MPMs , multiple MPMs in phased arrays, and towed decoys.

Folded waveguide TWT technology is being used to address EW requirements at frequencies above 40 GHz. RF output of 100 watts has been demonstrated with a folded waveguide TWT operating from 40 to 55 GHz. This design will be scaled to operate in the 85 to 100 GHz band Details of this development are shown in Figure 22.

For narrow band communication applications Northrop Grumman has developed an MPM that produces more than 180 watts of RF from 4 to 6 GHz with greater than 50% overall efficiency. The MPM has a volume of only 48 in^3 and is conduction cooled.



Performance of 40 to 55 GHz Folded Waveguide TWT That Is Being Scaled for an 85 to 100 GHz MPM (Figure 22)

Northrop Grumman summarized the opportunities and S&T needs for their VE device developments with the following statements:

Tremendous advances, compared with today's performance levels, are achievable with adequate research and development funding:

- 3X to 5X improvement in RF output power and efficiency
- 2X to 5X reduction in volume and weight
- Greater exploitation of frequency spectrum for advanced system concepts

Investment required in Vacuum Electronic devices:

- Advanced materials (i.e., windows, circuit support rods, etc.) to address thermal and RF power limitations
- Novel VE structures development (i.e., folded waveguide, modified helix) to provide higher power at higher frequency, stable operation of wider bandwidth, an d increased linearity at high efficiency
- Cold cathode/Wide band gap emitter development to open the opportunity of a new class of compact, highly efficient emission-gated devices
- Advanced materials for collectors to improve secondary emission and increase power capability
- Advanced VE modeling and simulation codes to reduce hardware experiments and ensure first pass success

Dr. Armand Staprans – Communications and Power Industries (CPI), Inc.

CPI's primary business is the production of Vacuum Electronic devices, which is about 80% of its sales. The remaining business involves subsystems incorporating VE devices. The past five years have seen a constant level of sales and employment. More than 50% of the company's RF VE business is for military applications.

CPI performs R&D and production in nearly every area of VE technology. The most significant developments are described below.

CPI is the largest supplier of broadband mini-TWTs, having delivered over 100,000 units. CPI's mini-TWTs have achieved an MTBF of over 80,000 hours in the SLQ-32 shipboard system environment. Development efforts to meet new military applications, such as towed decoys and advanced EW, includes doubling the RF power to 100 watts, increasing efficiency by incorporating multi-stage depressed collectors and providing high speed modulation capability.

The HT/MT Modernization Program takes the existing AN/FSC-78, AN/FSC-79 and AN/GSC-39 satellite communication (SATCOM) terminals and replaces the aging Radio Frequency (RF) electronics with new state-of-the-art hardware. CPI has developed a 2.25 kW CW helix TWT for the DoD HT/MT Modernization Program, specifically, the X-band Heavy Satcom Terminals. The RF power of this TWT has recently been increased to 2.5 kW for a NATO system. A dual C-X band TWT has been developed for the next generation military satcom terminals.

Millimeter wave helix TWTs that produce up to 125 W CW in the 27 to 30 GHz commercial communications band are being modified for low gain, high efficiency applications in MMPMs. Both radar and EW applications are being addressed.

A Ka-band coupled cavity TWT with approximately 1 kW pulsed output power has been qualified for use on a new missile seeker application. The performance requirements include very short pulse, high duty operation with limited cooling. CPI has completed a ManTech program to reduce the production cost by 50%.

CPI is developing extended interaction klystrons for radar, communications and science applications. Powers achieved include 150 watts peak at W-band and 1.5 kW at Ka band in very compact permanent magnet focused devices. Future goals include increased bandwidth of 4 to 8% and increased average power.

Multi-stage depressed collectors have been incorporated in communication klystrons operating at frequencies from S to Ka band. This has doubled the efficiency for linear operation.

The development of a 1 MW CW, 700 MHz, klystron for the Accelerator Production of Tritium (APT) program initiated a new generation of super-power devices. The design techniques developed under the APT were then used to develop a line of high power klystrons at UHF for scientific applications, ending foreign dominance in U.S. science VE applications.

CPI in collaboration with NRL, Litton and the University of Maryland, has developed a 100 kW peak, 10 kW average power gyro-TWT for next generation millimeter-wave high-resolution radar applications. This is an example of first pass design success on a state-of-the-art device that was enabled by advanced computer modeling and simulation codes.

Gyrotron oscillators developed for fusion energy research are now approaching cW power levels of 1 MW at 100 GHz. This required the development of bonding techniques for large CVD diamond output windows (up to 4 inches in diameter) to handle the high RF power. The diamond window technology also increases the bandwidth capability for other millimeter-wave VE applications.

CPI has made advances in three areas of cross-field devices. Small, lightweight coaxial magnetrons have been developed for instrument landing radars and missile seekers. The noise level of a CFA used in the SPY-1 radar has been reduced by 10 dB to better than 55 dBc/MHz. Also, an S-band injection-locked magnetron has demonstrated 13 dB “gain” and 50 MW peak power, suitable for HPM applications.

CPI is participating in the implementation and validation of the NRL developed beam optics and interaction codes, Michelle and Christine. These codes have contributed significantly to the recent advances in VE device performance, and full 3-D codes are a key enabler of future technology developments.

Beyond the evolutionary development of VE devices, there is also potential for revolutionary improvements, particularly in the area of high efficiency by use of advanced multi-stage depressed collectors. Funding should be directed to this area as well as improved 3D design codes, advanced materials and improved hot and cold cathodes.

CPI expressed concern about the erroneous perception among military systems designers that VE technology is obsolete compared to solid state. As a result, DoD funding of VE S&T is vanishing and VE technology is not being considered for some new systems. In reality each technology has areas of superiority, and they are complementary to each other.

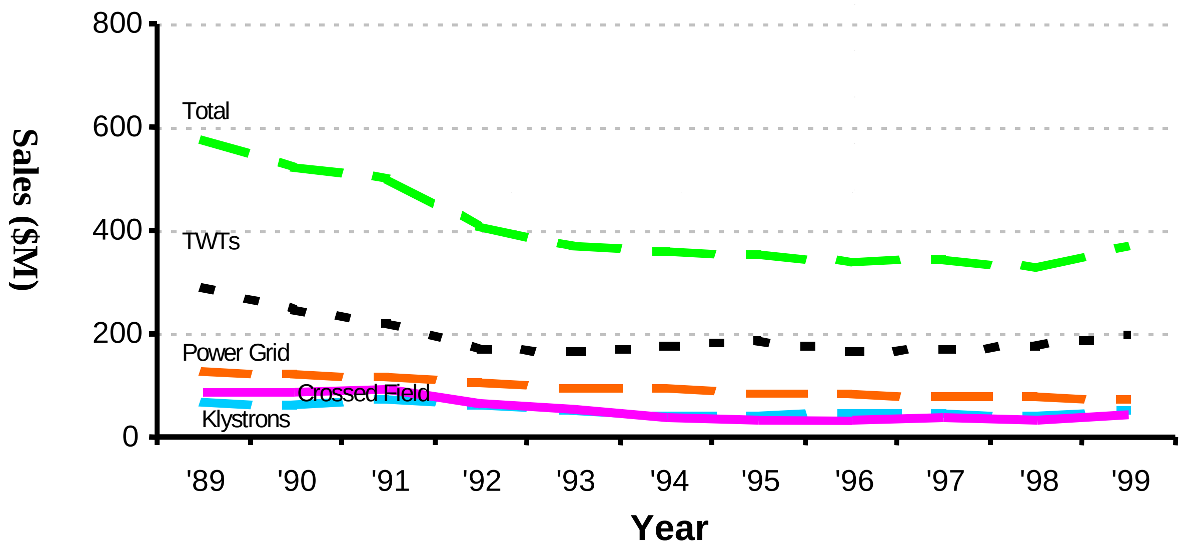
Another problem is the recruitment of engineers to replenish attrition of the VE technical staff. The universities are the primary source of new talent for the industry and Government labs. Increased Government support of university VE research and education programs can play an important role to insure that new engineers and scientists continue to be trained in this important technology.

Mr. Jon Christensen, Electronic Components Association -Vacuum Electronics Division

Mr. Christensen presented an overview of the U.S. Vacuum Electronics Industrial Base including products, markets, sales trends and DoD business challenges.

The U.S. Vacuum Electronics industry is comprised of approximately 20 companies. The four major VE companies, Communication and Power Industries, Inc, Litton Electron Devices Division, Boeing Electron Dynamic Devices, Inc, and Teledyne Electronic Technologies account for about 90% of the industries sales. These four companies are located in California and employ approximately 2000 people.

U.S. POWER TUBE INDUSTRY SALES



The U.S. Industry sales history is shown in Figure 23.
(Figure 23)

Sales of VE devices reached $600 million (including $130M sales of power grid tubes) in 1989 and decreased dramatically to $330 million (including $80M sales of power grid tubes) in 1997. Sales stabilized to about $350 million in the 1998 to 2000 time frame.

Seventy to seventy-five percent of U.S. industry sales are for military systems applications. A typical sales breakdown by device type for 1999 shows Klystrons 18%, CFAs and Magnetrons 11%, Coupled Cavity TWTs 20%, and Helix TWTs 52%. The European VE industry has a 13% market share in the U.S., mostly sales to OEMs, and a 33% market share world-wide.

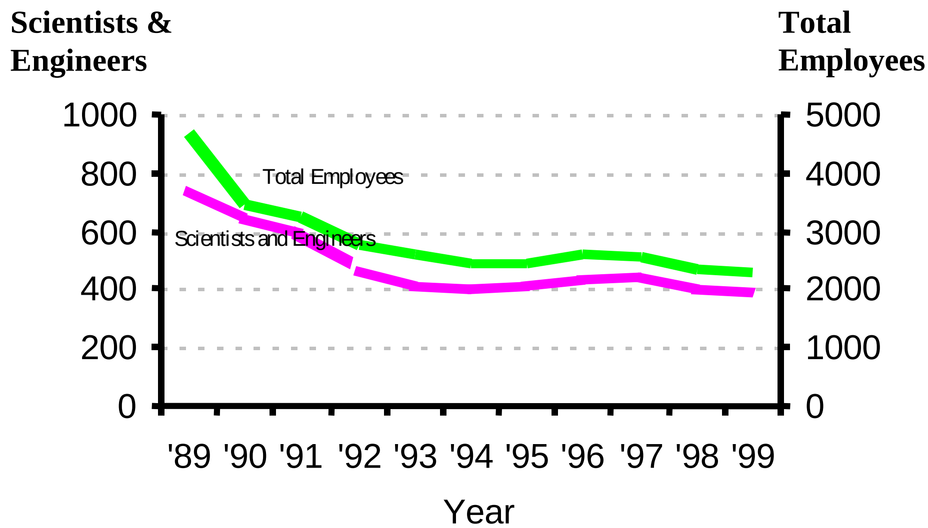
Industry sales for DoD applications are expected to stay relatively constant. However, military systems will remain the largest market for VE devices for the foreseeable future.

The VE industry is achieving significant advances in device performance, particularly in the areas of higher efficiency, higher RF power at millimeter-wave frequencies, improved linearity and much greater reliability. The development and use of computer modeling and simulation codes are accelerating the technology advancements and reducing the need for experimental iteration, thus reducing the development cost and time.

There is much greater industry interaction and collaboration with the DoD laboratories and the Universities that has maximized the efficient use of available resources and has produced excellent research and device performance.

VE industry staffing has closely followed the sales trends as shown in Figure 24.

U.S. POWER TUBE INDUSTRY EMPLOYEES



(Figure 24)

Total production employment reached approximately 4800 in 1989, including 750 scientists and engineers. This dropped to the current levels of 2200 total and 400 scientists and engineers. The VE industry is seeing a continual loss of experienced technical staff due to attrition, retirement and aggressive recruitment by commercial high technology industries. There are currently more than 60 openings for degreed professionals (an 18% shortfall). Nearly all new professionals are recruited from Universities. Industry is increasing its involvement in University research and educational programs to attract more students to the VE field.

The lack of sufficient DoD S&T funding to support Vacuum Electronics research and development is a major industry concern. The history of DoD funding for VE applied research and advanced development is shown in Figure 6, page 45.

In FY88, VE technology funding levels had fallen to $12.6 million (FY01 constant dollars). This level of support was considered seriously inadequate. To remedy this critical situation, OUSD(A)/DDR&E established and funded the tri-service/DARPA Vacuum Electronics Initiative, which was conducted in FY90 to FY95. This program produced outstanding technology advances that have been described throughout the VE STAR. Since FY95 the DoD funding has been reduced each year, reaching just $7.7M in FY01. This level of funding is well below the critical threshold to sustain vacuum electronics technology. At the $7.7M level there is negligible funding available for industry efforts to apply these technology advances to VE devices used in military systems.

The Navy, the lead center for VE under Reliance, provides nearly all the 6.2 and 6.3 funding for this technology; Air Force funding is less than $200K per year and there is negligible funding from the Army and DARPA. Unlike solid state technology, which has funding from many different sources, the Navy S&T program is the only source of funding for VE technology development.

ManTech funding is needed for infrastructure and producibility improvements to reduce the cost of VE devices for new and existing DoD systems. From 1990 to 1997 there were no ManTech

funds applied to VE. From 1998 to 2000 funding of $3.9M was provided for some Helix and CC TWT manufacturing improvements. These projects were successfully completed. However, there is no funding to address other important areas. MPM design and assembly processes must be improved in order to meet the cost goals for new ECM systems insertion. A $5M to $7M ManTech program for MPM producibility improvements and cost reduction is recommended.

A Title III Program has been funded to improve the sub-tier supplier base for the VE industry. Industrial base studies have currently identified 9 critical materials provided to the VE industry by small companies or where the supplied material/assembly is a very small niche material of a very large company. Materials/subassemblies include tungsten alloy tape and wire, cathodes and cathode assemblies, Berylia ceramics, copper nickel alloys, and rare earth magnets. Using the current funding, $5M, initial efforts have been started with the tungsten tape, tungsten filament and cathode companies. Continued funding is needed to address additional sub-tier supplier needs and assure their long term viability to meet the VE industry's and DoD's long term requirements. Current investments are with H Cross, Union City filament, Spectramat and Semicon

The industry is concerned about the apparent lack of knowledge within the DoD regarding the capabilities of VE technology. The VE transmitter design expertise is also eroding in the major OEMs. There are only two DoD laboratories that are conducting VE research and development, NRL Vacuum Electronics Branch, and NSWC Crane. Because of this knowledge gap, VE technology alternatives are not being considered during the initial system tradeoffs. The industry is working hard to educate the user community and military decision makers on the performance and cost advantages of Vacuum Electronics devices.

The DoD demand for VE devices will continue beyond 2050, with growing emphasis on millimeter-wave systems applications. DoD will continue to be the largest market (>60%) for the foreseeable future.

Future growth is projected in commercial telecommunications and communication satellite markets as the demand increases for bandwidth and personal communication services.

The markets for VE devices are becoming increasingly global, and there is more competition from foreign producers, particularly in Europe. The European industry has more Government R&D support and protection (given that the US does not give R&D support and protection to the VE manufacturing industry).

The US VE industry will continue to consolidate (Northrop Grumman is purchasing Litton EDD) as required by business demands.

The following actions are needed to maintain a strong, competitive VE technology base and to develop the high performance devices needed for future DoD systems and upgrades of existing systems:

- Increase VE S&T (6.2 and 6.3) funding to a minimum of $20M per year.
- Establish a $5-6M ManTech program for Microwave Power Module cost reduction
- Continue University VE research programs (6.1 and MURI) to sustain the highly successful technical and educational programs.
- Establish funding for upgrades of fielded VE transmitters to improve performance and reliability and to reduce operating cost.
- Develop new system concepts with architectures that can use either VE or solid state RF power devices.

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APPENDIX E: SUMMARY OF PRESENTED CURRENT MICROWAVE VACUUM ELECTRONIC DEVICE PERFORMANCE AND TRENDS

1. VE devices have demonstrated performance superiority in RF power-bandwidth product, efficiency and RF power production at frequencies above 20 GHz. Continued advances in VE in RF power and efficiency are projected due to the physics of the vacuum transport medium (near collision-less electron flow eliminates resistive losses and enables the beam energy to be recovered in the collector). Measured in terms of $P_{av}(f)^2$, a measure of average power density, the performance of VE technology doubles every 2 years (Figure A).

2. Ultra-wide bandwidth (3 to 18 GHz) performance with RF output power of >125 watts, and efficiency of 25% to 45% over the band, has been achieved with a Microwave Power Module developed for EW applications. By 2007 EW systems will need increased RF power of 200 watts and increased bandwidth of 2 to 18 GHz. To meet these requirements, development funding is needed to improve the designs of the major MPM components (Helix TWT, solid state RF driver and power conditioner).

3. Millimeter wave Helix TWTs are being produced with RF output power of more than 130 watts at 44 GHz and 40% efficiency. This is the highest $P_{av}(f)^2$ ever achieved with a Helix TWT.

4. Helix TWTs for communication satellite applications are achieving greater than 73% overall efficiency at frequencies up to 12 GHz. These devices have lifetimes of more than 18 years and in-orbit reliability of more than 10 million hours. This reliability is equal to or greater than solid state RF devices of lower power and efficiency.

5. Narrow bandwidth Microwave Power Modules have achieved 180 watts RF output power from 4 to 6 GHz with greater than 50% efficiency and 10 dB noise figure. The MPM package volume is 49 cu in. This performance is superior to solid state transmit modules that have been developed for similar applications.

6. A Folded Waveguide TWT has produced 50 to 100 watts over the frequency band of 40 to 52 GHz. This design is being scaled to operate at 85 GHz to 100 GHz. Computer simulations predict efficiency of greater than 30% using a velocity taper and multi-stage depressed collector.

7. An ultra-linear Helix TWT has been developed for commercial telecommunications applications. The TWT amplifier with linearizer provides 200 W RF at 1.8 to 2.0 GHz with C/3IM of –72 dBc. Operating at 10 dB backoff, the TWTA efficiency is about 20% including linearizer and power supply losses. The TWTA is capable of producing 500 W RF at 40% efficiency for operation at 6 dB backoff.

8. A Gyro-TWT device has achieved RF output power of 100 kW peak, 10 kW average at 94 GHz with 31% efficiency. Fast wave amplifier technology is advancing rapidly, due in large part to the development of improved computer simulation codes.

9. A Millimeter-wave Microwave Power Module has produced 20 to 40 watts CW over the entire 18 to 40 GHz frequency band. Development of an MMPM providing 50 watts over the band is underway. Operation with RF power output of 100 watts over the frequency band is expected by 2010.

10. The performance of ultra-wide band Helix TWTs continues to increase in both RF power and bandwidth. In 1996, RF power of 60 to 100 watts was achieved from 6 to 18 GHz. In 1999, RF power of 125 to 200 watts was produced from 3 to 18 GHz. The efficiency was 25% (band edge) and 45% (band center). The TWT gain was 27dB (band edge) and 47dB (mid band). For broad band applications such as MPMs, the RF drive is tailored to match the TWT gain variation, resulting in maximum RF over the band. Increased RF power of 200watts and bandwidth of 2 to 18 GHz using harmonic drive is projected by 2007. Similar performance increases are planned for Helix TWTs and MPMs operating from 18 to 40 GHz.

11. The efficiency of VE devices continues to increase with improvements in electron beam optics, depressed collectors and RF circuits. Efficiency of 73% has been demonstrated with a 100 watt, 12 GHz helix TWT with 500MHz bandwidth. Achievement of 76% efficiency is expected in 2001.

12. SLAC has successfully developed a PPM focused Klystron that produces 75 megawatts pulsed at X-band.

APPENDIX F: U.S. VACUUM ELECTRONICS INDUSTRY AND TECHNOLOGY BASE

1. The U.S. VE industry consists of four major manufacturers and many smaller producers. CPII, Northrop Grumman, Boeing EDD and Teledyne account for 90% of the industry sales. Northrop Grumman purchased Litton EDD in April 2001. U.S. industry annual sales has stabilized at around $280 M, down from a peak of over $500 M in 1988. Approximately 70% to 75% of the market is DoD systems applications.

2. The European VE industry has 13% share of the DoD market. Europe has a world market share of 35%, excluding VE sales by producers in Asia.

3. The U.S. VE industry employs approximately 2200 personnel (production and engineering), down from 3800 in 1988. There are currently about 390 engineers and scientists, down from 840 in 1988. The number of unfilled openings for technical professionals, which totals more than 65, is of concern. This is a shortfall of 17%. Universities are the primary source of engineers and scientists for the VE industry. There is strong industry demand for trained graduates.

4. U.S. industry is investing IRAD at 5 % to 7% of sales, or approximately $15M per year. Investments are primarily in the development of devices for commercial applications and to improve modeling and simulation capability.

5. Eight major U.S. Universities are involved in VE research. These activities involve 17 regular faculty, 30 research faculty and staff and 46 related faculty. There are currently 42 Ph.D. students and 21 M.S. students enrolled in VE studies and research. There is strong coupling with industry and Government laboratories and collaboration within the University community. DoD funding for University VE research is $3.375M. Non-DoD (primarily DoE) funding is $2.21M. Related funding (University facilities) is estimated at $7.5M per year.

6. The National Laboratories that support VE technology include Naval Research Laboratory, NSWC Crane, Stanford Linear Accelerator Center, Los Alamos, and NASA Glen Research Center. Under Project Reliance, the Navy was designated as the lead service for Vacuum Electronics R&D with the Naval Research Laboratory (NRL) being identified as the lead DoD laboratory. NRL planned, managed and directed the Tri-Service element of the Vacuum Electronics S&T Program with guidance and participation of a Tri-Service/DARPA steering committee. SLAC and Los Alamos primarily support DoE and HPM research and development.

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APPENDIX G: SPEAKER ATTRIBUTION TABLE

FINDING NO.	1. CA	2. Jday	3. RL	4. AS	5. JC	6. LV	7. RW	8. RDR	9. Jdut	10. EW	11. RL	12. JG	13. GC	14. NL	15. TA	16. RT	17. BL	18. JPL	19. RP
1	X	X	X	X	X			X		X	X	X	X			X			X
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3	X			X									X					X	X
4	X		X				X	X		X	X	X							X
5	X		X				X	X		X	X								X
6		X								X									X
7	X	X		X			X	X		X	X								X
8	X	X	X				X												X
9	X				X		X												X
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12	X	X	X	X		X	X	X			X	X	X						X
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E2	X		X								X								X
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F4					X														X
F5														X					
F6					X								X	X					

Note: This table indicates the specific presentations that addressed the Principal Findings and the additional Findings in Appendices E and F. All of the presenters have concurred with all of the Findings in this STAR Report.

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APPENDIX H: GLOSSARY

APBN	Anisotropic Pyrolytic Boron Nitride
ASCM	Anti-Ship Cruise Missile
CC-TWT	Coupled Cavity Traveling Wave Tube
CFA	Crossed Field Amplifier
CVD	Chemical Vapor Disposition
CWI	Continuous Wave Illuminator
EA	Electronic Attack
EIK	Extended Interaction Klystron
ERP	Effective Radiated Power
FEA	Field Emitter Array
HDR	High Data Rate
HPFOTD	High Powered Fiber Optic Towed Decoy
HPM	High Powered Microwave
IDECM	Integrated Defensive Electronic Countermeasures
ISAR	Inverse Synthetic Aperture Radar
JSSJ	Joint Service Support Jammer
ManTech	Manufacturing Technology
MBK	Multiple Beam Klystron
MEADS	Medium Extended Range Defense System
MMIC	Monolithic Microwave Integrated Circuit
MMPM	Millimeter-Wave Power Modules
MPM	Microwave Power Module
MTTF	Mean Time To Failure
MURI	Multi-University Research Initiative
PAM	Power Amplifier Module
PHEMT	Pseudomorphic High Electron Mobility Transistor
PMMA	Poly(methyl methacrylate)
PPM	Periodic Permanent Magnet
SAR	Synthetic Aperture Radar
SIRFC	Suite of Integrated Radio Frequency Countermeasures
SMART-T	Secure Mobile Anti-Jam Reliable Tactical-Terminal
SSA	Solid State Amplifier
SSEM	Solid State Electron Emitter
TBM	Tactical Ballistic Missile
TESAR	Tactical Endurance Synthetic Aperture Radar
TWT	Traveling Wave Tube
TWTA	Traveling Wave Tube Amplifiers
UAV	Unmanned Air Vehicle
VE	Vacuum Electronics

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